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Large-area mobile measurement of outdoor exposure to radio frequencies

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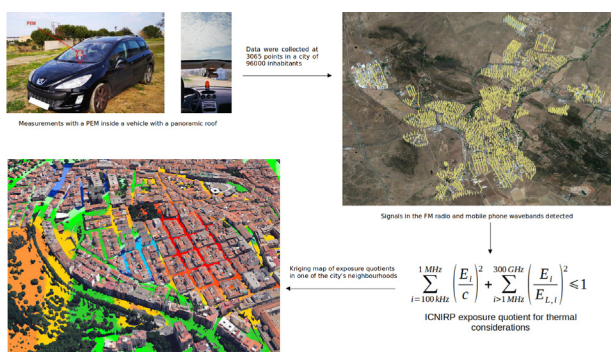
HIGHLIGHTS

- Fast car-mounted RF measurements in large urban outdoor areas.
- The car alters personal exposimeter measurements in a quantifiable way.
- Exposure quotients for thermal effects calculated in a multi-frequency environment.
- Fusion of RF exposure maps with aerial photographs.

GRAPHICAL ABSTRACT



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ABSTRACT

A rapid outdoor sampling technique was tested to measure human exposure to radio frequencies in a city of 96,000 inhabitants. The technique consisted of taking measurements with a personal exposure meter inside a moving vehicle. Tests were carried out to quantify the alteration produced by the vehicle's structure and obtain correction factors in order to minimize this alteration. Data were collected at 3065 points where signals in the FM radio and mobile phone wavebands were detected. The coefficients of exposure to sources with multiple frequencies due to thermal effects were calculated from the measured values of the electric field. Kriging was used to generate maps of these coefficients, and these maps were then merged with aerial photographs of the city to readily identify the areas with greater or lesser exposure. The results indicated that the vehicle increased the FM broadcasting radiation readings by a factor of 1.66, but attenuated those of mobile telephony by factors of 0.54–0.66. The mean electric field levels detected throughout the city were 0.231, 0.057, 0.140, 0.124, and 0.110 V/m for the frequency bands FM, LTE 800 (DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL), respectively. The mean coefficient of exposure to sources with multiple frequencies was 2.05×10^{-4}, and the maximum was 9.81×10^{-3}. It can be concluded from the study that it is possible to assess radio frequency exposure using this method, and that the technique is scalable to different sized cities. It also allows measurement at different times so as to analyse the temporal variation of radio frequency levels.

1. Introduction

The measurement of the exposure levels to radio frequency electromagnetic fields and their compliance with regulatory guidelines constitutes crucial information for epidemiological research as well as risk assessment, management, and communication.

Studies into human exposure to radio frequencies are performed routinely in many countries to assess compliance with regulatory guidelines. Examples of other objectives of this type of study are the classification of individual exposures (Bhatt et al., 2016), the quantification of exposure to different micro-environments (Sagar et al., 2018), the study of temporal and

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spatial trends in the levels of exposure to radio frequencies (Urbinello et al., 2014), and the analysis of the possible correlation of exposure to radio frequencies with the incidence of certain types of cancer (Gonzalez et al., 2017).

Radio frequency exposure is usually expressed in electric field units (V/m) or power density (W/m^2, mW/m^2, or μW/cm^2). Nonetheless, since the reference levels are frequency-dependent, accurate dosimetric evaluation requires that these values be weighted by reference levels. Also, in the case of multi-frequency environments it is necessary to use criteria of exposure to sources with multiple frequencies for electric and thermal effects – see for example the ICNIRP (1998) regulatory guide and its update (ICNIRP, 2020). The application of these criteria yields dimensionless coefficients that do not depend on the parameter chosen to characterize the exposure. Other studies similar to the present one are, for example, Paniagua et al. (2009) for the 0.5–2200 MHz frequency range which took into account both the electric and thermal effects, Rufo et al. (2018) which determined exposure coefficients in an area around an AM radio broadcasting antenna, and Paniagua et al. (2020) which used exposure coefficients from thermal effects of the frequency range 87–5850 MHz in a study of an urban area.

Some of the aforecited studies required measurements to be taken in large areas in relatively short time intervals. To this end, vehicle-based measurement systems were used as an alternative to traditional measurements made on a tripod. Thus, for example, Schiphorst and Slump (2010) used a fleet of mobile monitoring vehicles to extend the capacity of a fixed monitoring network in the Netherlands. Estenberg and Augustsson (2014) developed a vehicle-based measuring system that makes it possible to estimate the general public's exposure to radio frequencies in large areas through spectral measurements. Tell and Kavet (2014) also tested car-based mobile measurement systems for exposure studies. Bolte et al. (2016) evaluated the possibility of using a vehicle-mounted RF measurement device to monitor the radio frequency spectrum. Finally, Cansiz et al. (2016) obtained the characteristics of the electromagnetic environment in Diyarbakır (Turkey) by carrying out measurements with a high-precision spectrum analyser and an isotropic antenna mounted on the roof of a vehicle.

In the cited works, researchers normally present their results using descriptive statistics. In order to present the measured data in an easily understandable way, other investigations generate maps from data obtained by different sampling techniques. For example, Azpurua and Dos Ramos (2010) in Caracas (Venezuela), Aerts et al. (2013) in Ghent (Belgium), and Sánchez-Montero et al. (2017) in Alcalá de Henares (Spain) used static broadband measurements. Moving measurements with personal exposure meter (PEM) were performed by Gonzalez-Rubio et al. (2016) in Albacete (Spain), using a bicycle, and by Koppel and Hardell (2022) in Columbia (USA), walking. In all of them they present maps of the total field.

The main objective of the present work was to evaluate human exposure to RF-EMF through rapid sampling of georeferenced data in the city of Cáceres (Spain) which, according to the 2020 census, has 96,467 inhabitants. Measurements were taken outdoors throughout the city using a personal exposure meter set up inside a vehicle with a panoramic roof. The PEM breaks down the information by frequency bands, which provides more detailed information on exposure, and allows us to calculate exposure using regulations whose reference levels are frequency dependent. The use of georeferenced data allowed us, in addition to applying descriptive statistics as is done in most studies, to know the spatial distribution of the exposure values. Possession of this information is important, since it makes easier for us to know the places with the highest levels of exposure and, where appropriate, carry out a more exhaustive evaluation in the areas where people spend more time.

2. Material and methods

The study was carried out between October 2019 and March 2020 in the city of Cáceres (Spain). This city is located in west-central Spain, with geographic coordinates 39°28′ N, 6°22′ W, at 430 m above sea level. There are >80 sites in the city with mobile telephony antennas that in many cases share different technologies and operators.

The locations of the antennas are shown in Fig. 1 (yellow). There are also FM radio antenna sites on the outskirts of the urban area (in red in

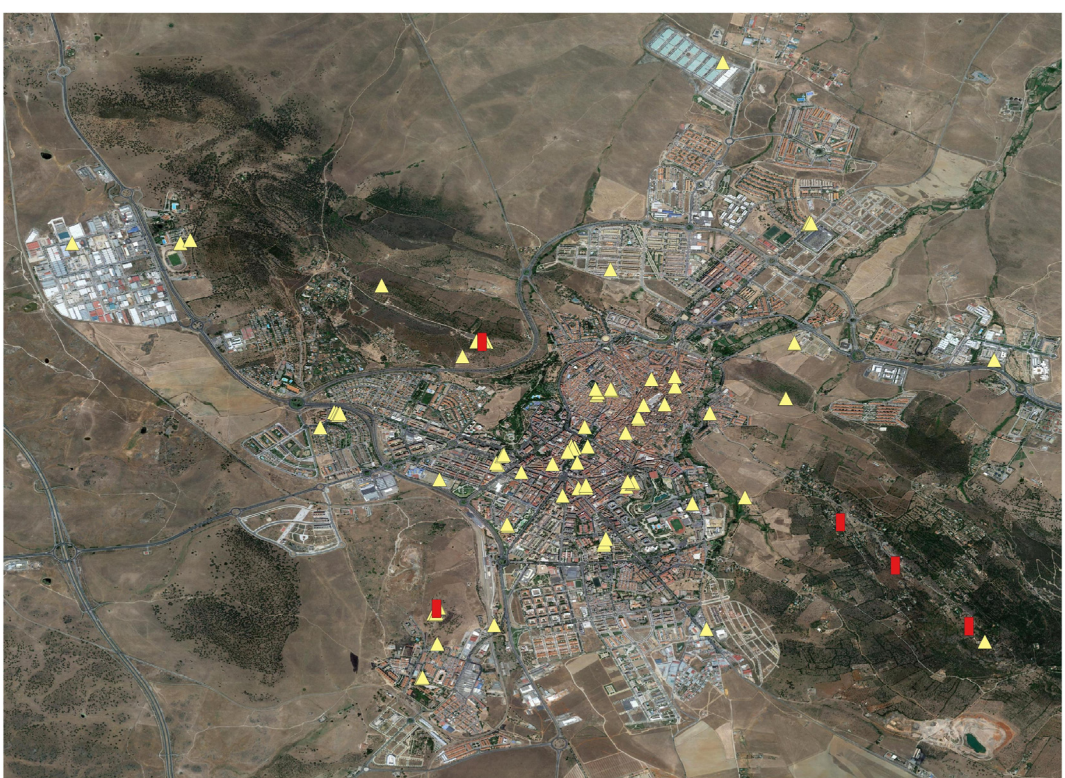


Fig. 1. Mobile telephony (yellow) and FM radio (red) antennas in the city of Cáceres.

Fig. 2. Left: Exterior view of the vehicle with the exposure meter. Right: View of the position of the PEM from inside the vehicle with the panoramic roof open.

the figure). It is interesting to highlight the high power of FM radio antennas, with ERP (effective radiated power) values of around 5–6 kW.

The measurements were made with an exposure meter set up inside a vehicle. This vehicle was a Peugeot 308 SW 1.6 Turbo HDI 16 V 110 CV of the year 2009 with 220,000 km milage, dimensions 4500 × 1815 × 1556 mm (length, width, height). It had a 1.68 m^2 panoramic glass roof that ensured great visibility and luminosity. Fig. 2 shows the vehicle with the position at which the exposure meter was placed during the measurements.

2.1. Exposure meter

The exposure meter used was the EME SPY 200 (Microwave Vision Group, 2022). It is a light and portable dosimeter, with dimensions of 168.5 × 79 × 49.7 mm and a weight of 440 g. It consists of three orthogonal *E*-field isotropic probes that perform continuous measurements of the level of electromagnetic fields in 20 pre-defined frequency bands in the frequency range of 87 MHz–5.85 GHz. It allows measurements to be carried out by storing a maximum of 80,000 data points with a recording interval of from 4 to 255 s. It has a button to set marks while taking measurements. It also has an integrated GPS to georeference the measurements. Table 1 lists the technical characteristics of this PEM, including the frequency bands, the sensitivity, and the standard uncertainty due to axial isotropy in the vertical plane in each band.

Through the EME Spy Evolution mobile app, a cellphone–dosimeter link was created via Bluetooth through which to configure the dosimeter. Once the measurement parameters had been configured, the instrument worked autonomously. At the end of the measurement process, a file containing the georeferenced electric field data was created in the mobile device.

2.2. Data acquisition

With the dosimeter set up vertically on the centre of the vehicle's dashboard, the panoramic roof open, and two people (driver and passenger) inside the vehicle, we travelled through each of the areas or neighbourhoods of the city trying to maintain a constant speed of 30 km/h, taking a sample every 6 s (equivalent to an approximate distance of 50 m). It required 17 trips to cover the entire area studied, all made on weekdays during the time slot from 9:00 a.m. to 2:00 p.m., with durations varying from 30 to 150 min depending on the size of the area, traffic, etc. The total sampling time was about 13 h without counting the journey from the laboratory to the sampling area.

It was not always possible to maintain the 30 km/h speed due to stops at traffic lights, pedestrian crossings, traffic jams, etc. The density of points obtained was therefore not regular throughout the city. For this reason, the measured values were subjected to a data cleansing process, exporting the file generated by the EME Spy Evolution app to the QGIS software package (QGIS Development Team, 2022). This allowed the points where we had captured the data to be displayed on an aerial photograph of the area. As an example, the left part of Fig. 3 shows an image of an area of the city together with the data collection points. It shows that in some places the data has been acquired at regular intervals, but in others there is excessive accumulation of points due to the reasons noted above. With the help of the labelling options that QGIS allows, we eliminated measurements at points very close to others in order to obtain a more regular distribution (Fig. 3, right). This data cleansing procedure left a total of 3065 points distributed throughout the city (Fig. 4). The total area sampled was 11.88 km^2, with a density of 258 points/km^2.

2.3. Vehicle attenuation

As indicated above, the data acquisition was carried out with the PEM located inside a vehicle. This sampling procedure was expected to alter the electric field readings compared with measurements made on the tripod. We therefore designed an experiment to analyse these alterations and find correction factors.

Table 1
Technical characteristics of the PEM EME SPY 200 (TETRA: Terrestrial Trunked Radio, LTE: Long Term Evolution, GSM: Global System for Mobile Communications, DECT: Digital Enhanced Cordless Telecommunications, UMTS: Universal Mobile Telecommunications System, WiMax: Worldwide Interoperability for Microwave Access, UL: Uplink, DL: Downlink).

Frequency band	F_{min} (MHz)	F_{max} (MHz)	Sensitivity L (V/m)	Axial isotropy Vertical (±dB)
FM	87	107	0.010	0.1
TV3	174	223	0.010	0.5
TETRA I	380	400	0.010	0.2
TETRA II	410	430	0.010	0.5
TETRA III	450	470	0.010	0.5
TV4&5	479	770	0.010	0.3
LTE 800 DL	791	821	0.005	0.3
LTE 800 UL	832	862	0.005	0.3
GSM + UMTS 900 UL	880	915	0.005	0.3
GSM + UMTS 900 DL	925	960	0.005	1.0
GSM 1800 UL	1710	1785	0.005	1.2
GSM 1800 DL	1805	1880	0.005	1.2
DECT	1880	1900	0.005	0.9
UMTS 2100 UL	1920	1980	0.005	0.6
UMTS 2100 DL	2110	2170	0.005	0.8
Wi-Fi 2G	2400	2483.5	0.005	0.6
LTE 2600 UL	2500	2570	0.005	0.9
LTE 2600 DL	2620	2690	0.005	0.9
WiMAX	3300	3900	0.005	2.2
Wi-Fi 5G	5150	5850	0.010	2.2

Dynamic: 61.6 dB (up to 6 V/m).

Fig. 3. Aerial photography with raw sampling points (left) and after data cleansing (right).

The experiment was conducted on the university campus in Cáceres (Spain) at a place in line of sight to a group of mobile telephony antennas (located 280 m away) and to three FM radio antennas (about 2–3 km distant). One measurement was made with the exposure meter on the tripod and four measurements with it inside the vehicle – at angles of 0° (vehicle oriented towards the location with mobile phone antennas, which coincides with the direction west), 90° (north), 180° (east), and 270° (south). The measurements inside the vehicle were carried out with the engine running, panoramic roof open, and with two people inside (driver and passenger).

All measurements were made for 2 min registering a reading every 6 s, so that, for the statistics, there were 20 data points for each orientation. This experiment was repeated thrice (the first at the beginning of sampling, the second in the middle, and the third at the end) at the same location in order to obtain robust final correction factors. Great care was taken for both the point and the height of the PEM above the ground to be the same.

2.4. Dosimetric evaluation

From the data collected by the exposure meter in V/m we can obtain exposure coefficients using existing regulations, such as those of the Federal Communications Commission (FCC, 1997) or the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998). The reference levels of these standards are based on thermal effects. Although a substantial scientific literature documents adverse biologic effects below the thermal threshold adopted by them, as pointed out by the International Commission on the Biological Effects of Electromagnetic Fields (ICBE-

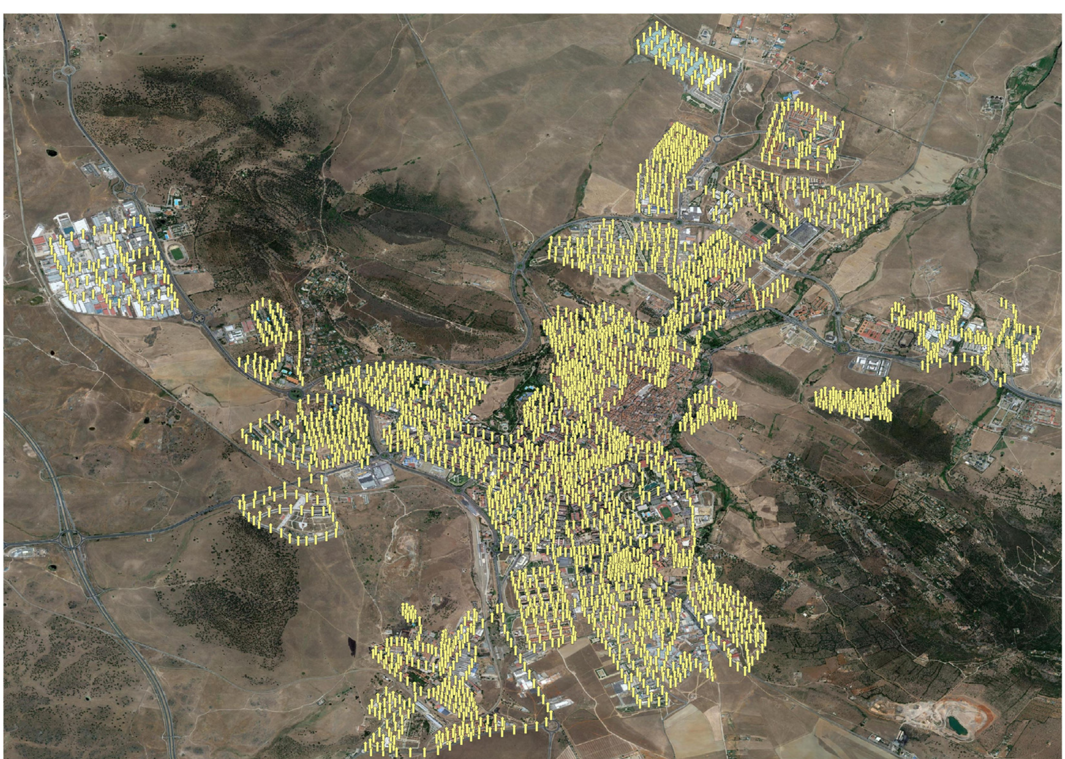


Fig. 4. Aerial photograph of the city of Cáceres with the sampling points (yellow arrows) after data cleansing.

EMF, 2022), in this work we used reference levels of existing regulations, specifically those of the ICNIRP, which are those adopted in Spanish legislation (AE, 2001). One advantage of having electric field levels is that they can be compared with the reference levels of any future regulations in order to carry out a dosimetric evaluation.

In a multi-frequency environment, to evaluate exposure it is necessary to take into account all the wavebands present. To this end, the ICNIRP proposes that for thermal considerations, relevant above 100 kHz, the following requirement should be applied to the field levels:

$$\Sigma_{i=100kHz}^{1MHz}\left(\frac{E_i}{c}\right)^2 + \Sigma_{i>1MHz}^{300GHz}\left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1 \qquad (1)$$

where E_i is the intensity of the electric field at frequency i, $E_{L,i}$ is the reference level for the electric field at that frequency, and $c = 87/f^{1/2}$, where f is the frequency expressed in MHz. This summation formula assumes worst-case conditions among the fields from the multiple sources (ICNIRP 98).

2.5. Maps

Two types of graphical representations of georeferenced data were used in this study. Firstly through graduated symbols using the QGIS software package (QGIS Development Team, 2022). The purpose of this technique is to easily visualize the spatial distribution of electric field intensity levels in the city, and identify the areas with the highest and lowest values of the field.

Secondly, through interpolated surfaces using block kriging (Cressie, 1993) after fitting a theoretical spherical variogram to the experimental variogram, and merging the resulting map with a Google Earth aerial image of the area. For this, we used the Google Earth “image overlay” option, entering the map limit coordinates and activating the “3D Buildings” option. The colour palette chosen, ranging from Maya Blue to Red, was taken from the ITU-T K.113 recommendation (ITU-T, 2015). According to this recommendation, the lowest colour of the palette should be applied to levels corresponding to <1 % of the maximum allowed, and the highest to those that are >100 %.

3. Results

3.1. Measurements

After cleansing the data as explained in Section 2.2, we had information for 3065 points distributed throughout the city. As usual when working with this type of exposure meter, radio-electrical activity was not detected in all bands. Fig. 5 shows the percentage of the data that surpassed the limit of detection L (sensitivity in Table 1) in each frequency band of the exposure meter.

As can be seen in the figure, the greatest percentages corresponded to the FM band (100 %) and the downlink (DL) mobile telephony bands GSM + UMTS 900, UMTS 2100, GSM 1800, and LTE 800, with 98.3 %, 95.2 %, 93.5 %, and 87.3 %, respectively. In the LTE 2600(DL) mobile telephony band, 24.1 % of the values were above the limit of detection. The uplink (UL) mobile telephony bands had very low “detected” percentages except that of GSM 1800 with 35.3 %. The DECT band, in which wireless telephony emissions are registered, had 72.4 %. Less activity was recorded for the bands of 2G (15.6 %) and 5G (3.0 %) WiFi and TV4_5 television (10.0 %). Finally, TETRA I (Terrestrial Trunked Radio, the personal communication system used in Europe for police and emergency services) had 18.7 %.

In view of these data, we focused our study on the band of sound broadcasting (FM) and those of mobile telephony with high detected percentages – LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL). For the treatment of “non-detected” cases, we resorted to the so-called naïve approach (as is used by default in the EME SPY 200 software). This consists of substituting the non-detects by the exposure meter's sensitivity of the band as listed in Table 1. Given the high percentages of “detected” in the frequency bands that we shall be considering, this relatively simple method does not lead to much loss of accuracy compared with other higher-order substitution methods (Bolte, 2016).

3.2. Influence of the vehicle on the measurements

Fig. 6 shows, by way of example, the electric field levels measured inside the vehicle, with angle 0° in the first experiment. This 120 s measurement yielded a 0.579 V/m mean value of the FM band electric field. In the LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL) mobile telephony bands the values were 0.051, 0.062, 0.120, and 0.020 V/m, respectively.

One observes in the example shown in Fig. 6 that the LTE 800(DL) and GSM 1800(DL) bands presented greater fluctuations than the rest. This was the case in all 12 tests carried out (three experiments of four orientations each). Considering the tests together, the mean relative standard deviations were 4.5 % for the FM band, and 27.4 %, 12.2 %, 32.0 %, and 14.7 % for the LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL) mobile telephony bands, respectively.

In order to compare the above values with the standard uncertainty as provided by the manufacturer, it is useful to express those values logarithmically through the equation $\sigma(\text{dB}) = 20 * \log[1 + \sigma(\%)/100]$ (Vulevic and Osmokrovic, 2010). This equation relates the relative standard deviation to the standard deviation in dB. The result gives values of 0.4 dB for the FM band, and 2.1, 1.0, 2.4, and 1.2 dB for the LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL) mobile telephony bands, respectively. These values are greater than the axial isotropy in the vertical plane for these bands (see Table 1).

Fig. 7 shows the electric fields detected with the PEM on the tripod and with it inside the vehicle for different orientations in the first experiment. For the sake of clarity, only the data of three frequency bands (FM radio, GSM1800(DL) and UMTS2100(DL) mobile telephony) are shown. The error bars indicate the standard deviation of the two-minute measurements.

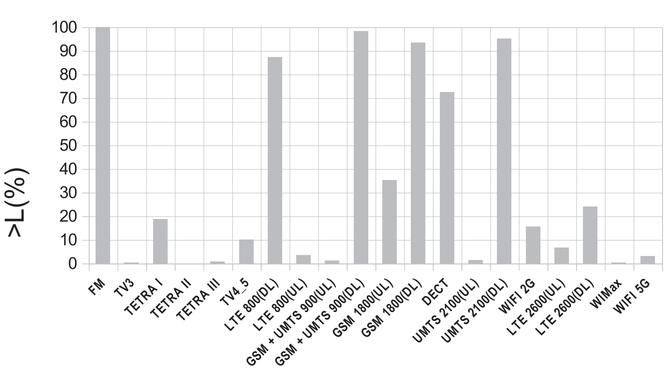


Fig. 5. Percentage of measurements that exceeded the PEM's limit of detection (L).

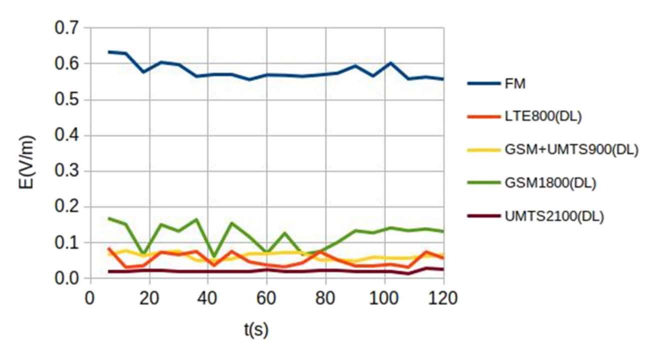


Fig. 6. The FM and mobile telephony band electric field levels detected inside the vehicle with orientation 0° in the first experiment.

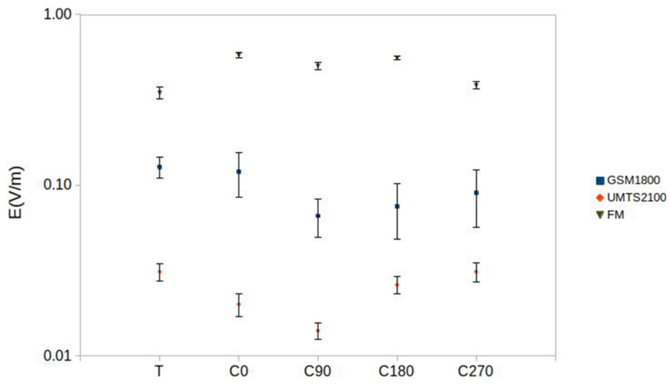


Fig. 7. Electric field levels detected with the PEM on the tripod (T) and with it inside the vehicle at different orientations (C0, C90, C180, and C270) for three frequency bands.

Table 2
Ratios (F) between the measurements made inside the vehicle and those on the tripod. Also listed are the standard uncertainty for axial isotropy in the vertical plane given by the manufacturer and the standard deviation (σ) in various units.

	F	σ	σ (%)	σ (dB)	Axial isotropy vertical (dB)
FM	1.66	0.34	20.9	1.6	0.1
LTE800(DL)	0.66	0.22	34.0	2.5	0.3
GSM900 + UMTS900(DL)	0.57	0.19	34.0	2.5	1.0
GSM1800(DL)	0.54	0.18	32.9	2.5	1.2
UMTS2100(DL)	0.58	0.18	31.2	2.4	0.8

One observes in the figure that, for the FM radio band, the values inside the vehicle are greater than those outside it (with the exposure meter on the tripod). This was the case for the three experiments carried out, and indicates that the vehicle's structure increases the electric field values detected in this band. For the mobile telephony band however, the opposite was the case with the values detected inside the vehicle being lower than those detected on the tripod. This was the same for the other three mobile telephony bands studied, indicating attenuation of the radiation coming from outside.

To quantify how the vehicle altered the measurements, we used the ratio of the electric field detected inside the vehicle to that detected on the tripod. Table 2 lists the mean values of these ratios (F) for the three experiments together, the standard deviation expressed in various units, and the standard uncertainty due to axial isotropy in the vertical plane (Table 1). One observes in this Table 2 that the ratio (F) is less than unity in the case of mobile telephony bands, with values between 0.54 and 0.66, but greater than unity (1.66) for the FM band. The standard uncertainties are 1.6 dB for the FM band and around 2.5 dB for the telephony bands.

With this quantification of the effect of the vehicle on the measurements, the data to be presented in the following sections will be corrected by the F factors given in Table 2.

3.3. Extensive sampling

As indicated above, after the data cleansing, there remained 3065 data points available for the statistical analysis. Table 3 lists the statistics of the electric field data for the frequency bands considered in this study. The band with the greatest electric field values is FM. There follow the mobile telephony bands GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL), and finally LTE 800(DL). The mean values obtained for these bands are 0.231, 0.140, 0.124, 0.110, and 0.057 V/m, respectively. Other statistical parameters, such as the median and percentiles, confirm the above.

With respect to the maximum values, relatively intense values (up to 3.8 V/m) were detected for the GSM + UMTS 900(DL) band. Nonetheless, these values were sparse since, as indicated by E_{95}, 95 % of the values detected in the mobile telephony bands were below 0.5 V/m, and in the FM radio band below 0.7 V/m.

Whether it is characterized by the relative standard deviation (σ/E_{avg}) or by the interquartile range divided by the median (IQ/E_{50}), the dispersion of the data is high – greater than 100 % for all bands. This reflects the breadth of the area sampled, with points close to and far from the emitters and surrounded by buildings that sometimes prevent direct line-of-sight and sometimes not.

The latter is evident when visualizing the spatial distribution of the electric field values detected in the city. As an example, Fig. 8 shows these distributions for the five frequency bands using the QGIS software with graduated symbols corresponding to the quartiles. The colour yellow represents the greatest values between E_{75} and E_{max}, and indigo represents the smallest between E_{min} and E_{25} (see Table 3).

Fig. 8 shows that there are major variations in the electric field levels even in small areas. The different spatial structures of the FM band and the mobile telephony band data is also evident. In the upper part of the figure, one observes that the greatest FM values are located in the east of the city, especially in the south-east. This reflects the influence of the FM radio broadcasting antennas that are located on the hill south-east of the city (see Fig. 1). On the contrary, the spatial distributions of electric field strengths in the mobile telephony downlink bands are similar to each other, and different from those of FM radio. The high values are more evenly distributed throughout the city as a consequence of the fact that the mobile telephony antennas are also evenly distributed (see Fig. 1).

3.4. Exposure evaluation

Using the first term of the inequality (1) (Section 2.3), one can evaluate the exposure due to thermal effects of the multiple-frequency sources from the electric field values detected in the different frequency bands. Dividing the field measured at frequency i, E_i, by the reference level for that frequency, $E_{L,i}$, one has the contribution to the exposure of that frequency band, denoted by EQ. The reference levels are 28 V/m for the FM radio band, 39.0 V/m for LTE 800(DL), 42.2 V/m for GSM + UMTS 900(DL), 59.0 V/m for GSM 1800 (DL), and 61.0 V/m for UMTS 2100(DL) (ICNIRP, 1998).

Table 4 lists the statistics of the exposure coefficients (EQ) for each of the frequency bands analysed and the total exposure coefficient. The mean exposure values were 145×10^{-6}, 5.8×10^{-6}, 32×10^{-6}, 13×10^{-6}, and 8.7×10^{-6} for FM, LTE 800(DL), GSM + UMTS 900 (DL), GSM 1800(DL), and UMTS 2100(DL), respectively. The mean total exposure from those five bands was 205×10^{-6}. Hence, radiation from FM radio transmitters contributes 66.3 % to the exposure, while that from mobile telephony does so with 33.7 %, in particular, 4.3 %, 16.8 %, 6.8 %, and 5.8 % for the LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL) bands, respectively.

Table 3
Statistics of the electric field measurements in the city of Cáceres in the FM radio band and in the DL mobile telephony bands. E_{25}, E_{50}, E_{75}, and E_{95} are the 25th, 50th, 75th, and 95th percentiles, respectively. IQ: interquartile range. R: range. Sample size: 3065.

E (V/m)	E_{avg}	σ	E_{min}	E_{25}	E_{50}	E_{75}	E_{95}	E_{max}	IQ	R
FM	0.231	0.246	0.010	0.082	0.148	0.280	0.704	2.471	0.198	2.461
LTE 800	0.057	0.075	0.008	0.014	0.031	0.068	0.195	0.756	0.054	0.748
GSM + UMTS 900	0.140	0.195	0.009	0.043	0.085	0.165	0.421	3.801	0.122	3.792
GSM 1800	0.124	0.171	0.010	0.034	0.073	0.145	0.414	3.615	0.111	3.605
UMTS 2100	0.110	0.142	0.009	0.032	0.064	0.130	0.366	1.775	0.098	1.766

Fig. 9 (center) shows the kriging interpolated map of exposure coefficients merged with the aerial image of the city (Fig. 9, top). As indicated in Subsection 2.5, the colour coding for displaying RF-EMF map levels is the one given as an example in Recommendation ITU-T K.113 (ITU-T, 2015). However, given that in this work no value exceeded 1 %, the above scale would have yielded a single colour map – the bottom of the scale. We therefore modified the colour scale to be able to appreciate the differences between the different parts of the city. The figure can be enlarged to obtain images like that of Fig. 9 (bottom) showing the buildings rising above the map. This very visual representation allows one to know the exposure at any point in the city with precision.

4. Discussion

In this work, we set out to study personal exposure to radio frequencies in a city of about 96,000 inhabitants by performing rapid sampling with a PEM located inside a vehicle. As a consequence, we have developed a rapid outdoor sampling technique and characterized that city in terms of exposure to radio frequencies.

4.1. Detected data

Several aspects were taken into account in analysing the results generated in this study. Firstly, the frequency bands in which more activity was

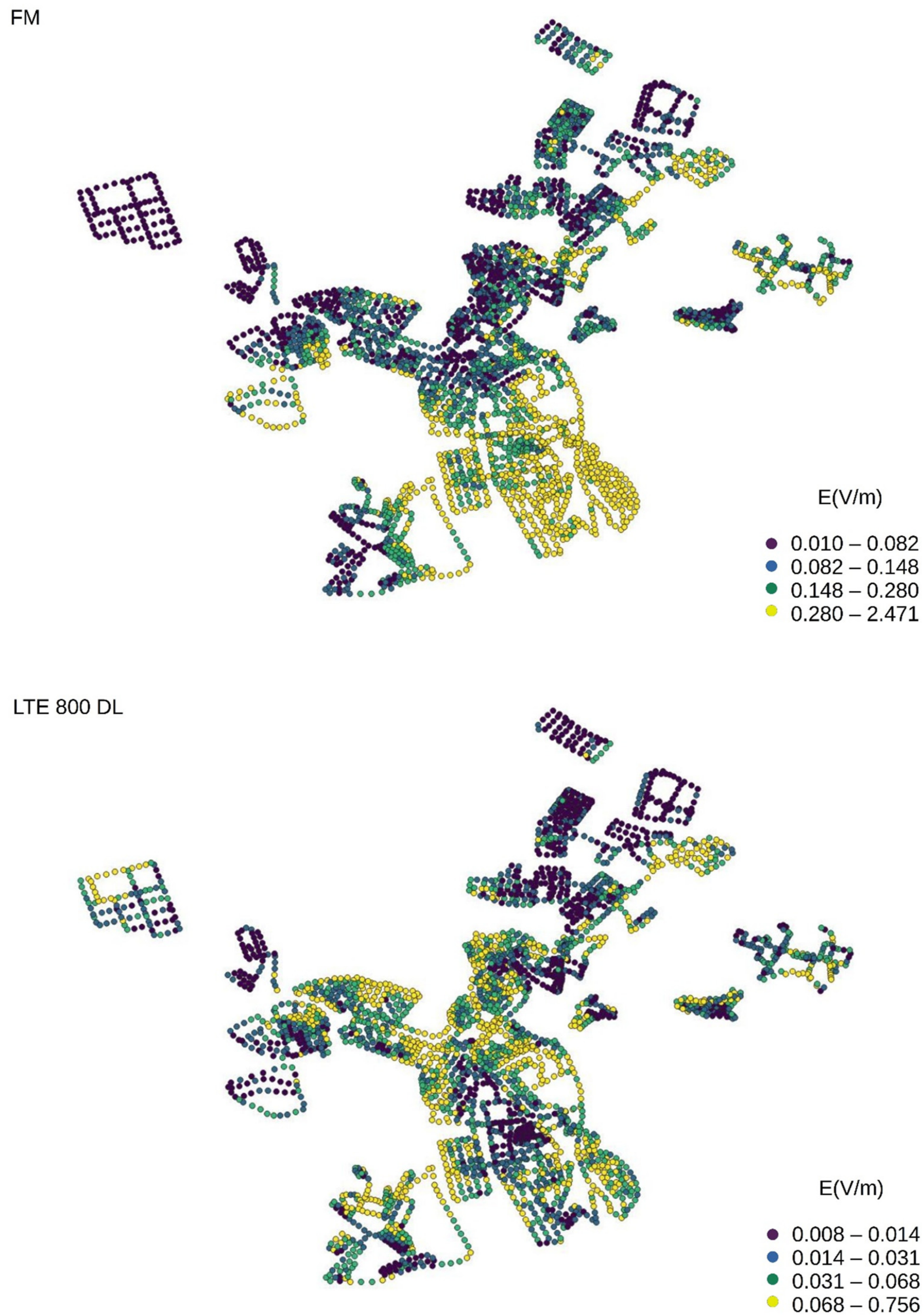
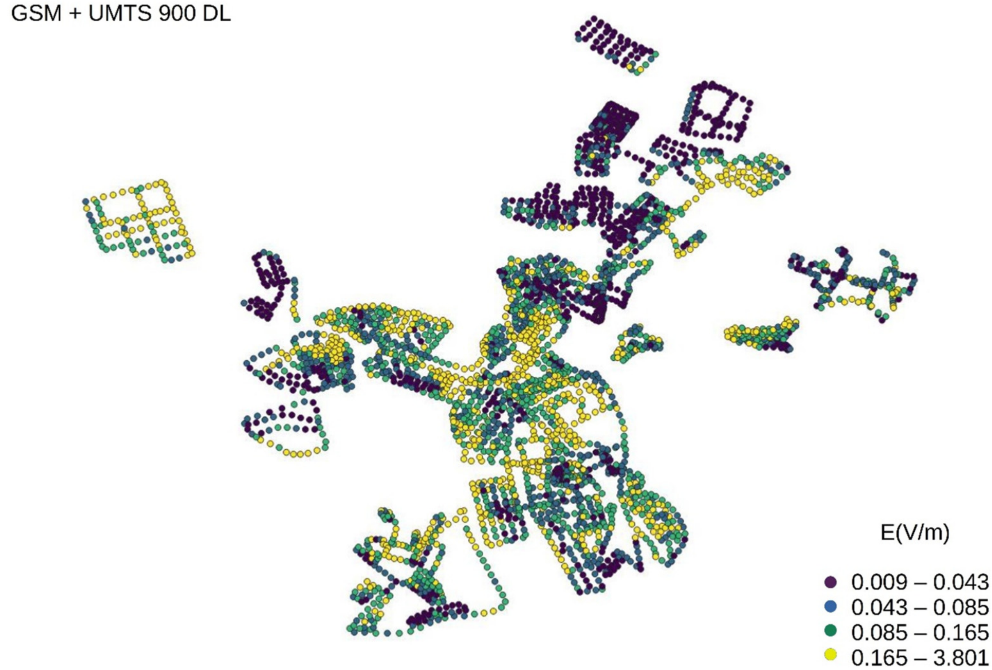


Fig. 8. Spatial distributions of electric field levels in the FM, LTE 800(DL), GSM + UMTS 900(DL), GSM 900(DL), and UMTS 2100(DL) bands in the city of Cáceres.



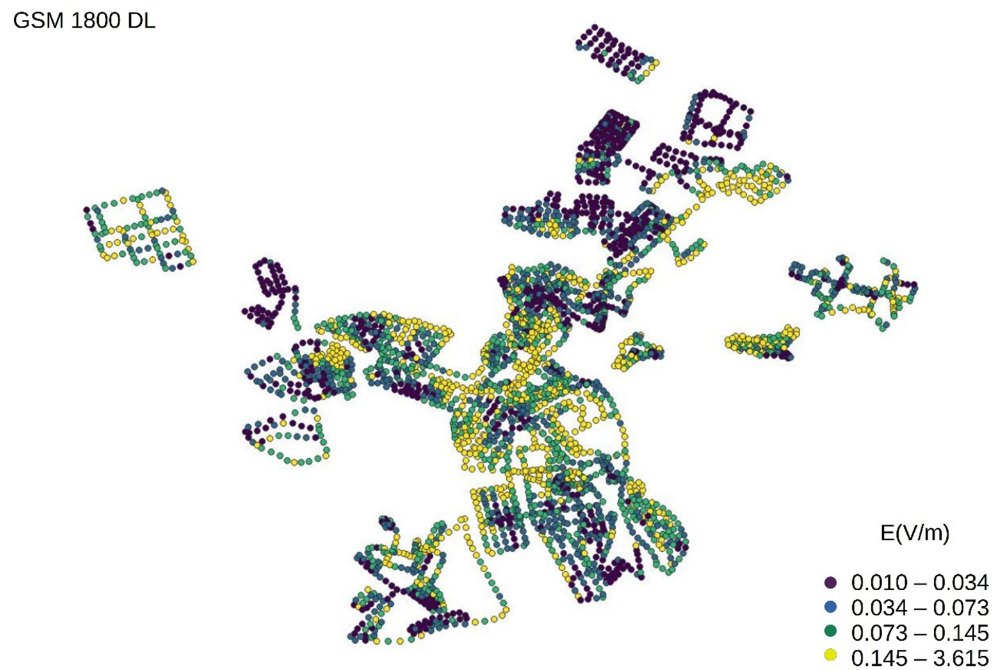


Fig. 8 (*continued*).

registered were those of FM sound broadcasting and the mobile telephony bands denominated in the EME SPY 200 PEM as LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL). These bands are shared by different operators and different generations of mobile telephony. In Spain, 4G/LTE is in the 800 MHz band, 2G/GSM and 3G/UMTS are in the 900 MHz band, 2G and 4G are in the 1800 MHz band, and 3G is in the 2100 MHz band (Orden ETD/1449/2021, n.d.).

The LTE 2600(DL) mobile telephony band includes the 4G/LTE technology. It had a low detected percentage, 24.1 %, indicating that there was little implementation of 4G technology in this band in the city of Cáceres when the experimental part of this investigation was carried out.

The DECT band, where wireless telephony emissions are registered, had a high percentage of detected values, 72.4 %. When sampled outdoors, the emissions recorded in this band are unlikely to have come from cell phones. It is more likely to have been a consequence of a cross-talk effect with the GSM 1800(DL) band due to the fact that they are contiguous. This phenomenon has been documented in other studies (Lauer et al., 2012; Bhatt et al., 2016).

The TV4–5 band had 10 % detected, a low value probably because the transmitters located in the city have little power. Although this power is sufficient to provide television coverage to homes whose receiving antennas are located on the roofs and terraces of the buildings, it provides little signal at ground level. The WiFi bands also registered little activity, 15.6 % for 2G and 3.0 % for 5G. This is a consequence of the emitting devices usually being inside homes and the sampling being carried out outdoors.

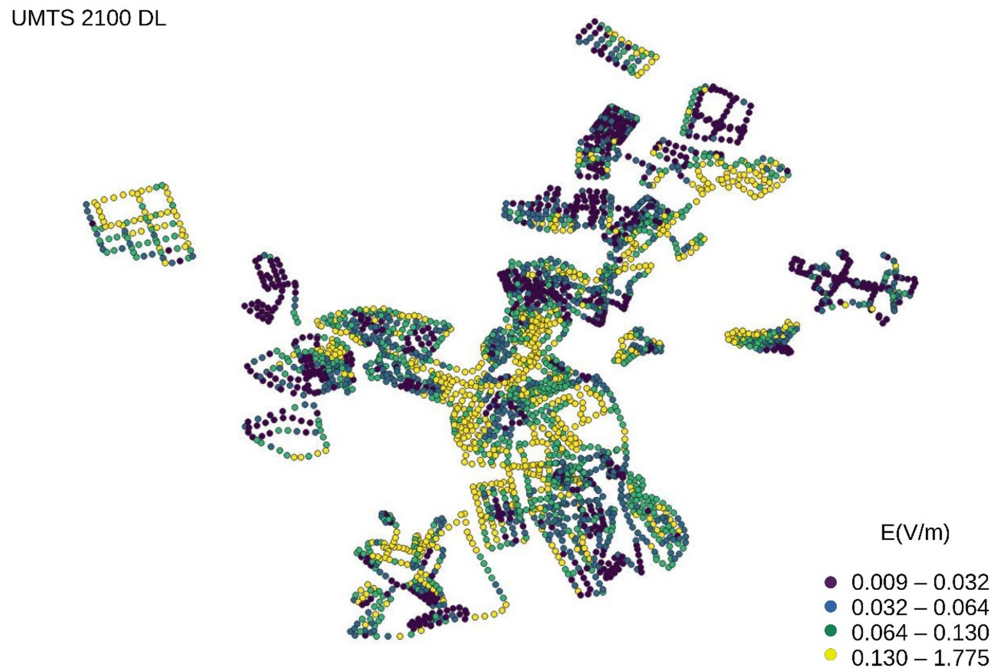


Fig. 8 (*continued*).

4.2. Influence of the vehicle

When studies are carried out with PEMs, one factor that must be taken into account is the alteration in the measurements caused by the person or vehicle carrying them. Various studies have quantified the alterations caused by different variables (Bolte et al., 2011; de Miguel-Bilbao et al., 2015; Bolte et al., 2016). They show that each case needs to be studied individually. We verified this experimentally in our previous work (Paniagua et al., 2020) also conducted in the city of Cáceres. In it, the sampling was done with the same EME SPY 200 exposure meter held in the operator's hands. In that work, we verified that the human body alters the measurements, sometimes attenuating them and sometimes augmenting them.

The experiment described in Section 3.2 was needed to analyse the alterations in the measurements produced by the body of the vehicle, and subsequently correct the values of the field registered in the different frequency bands. We found that inside the vehicle the FM band was augmented on average by a factor of 1.66. The cause is likely to have been that the wavelength of the radiation, approximately 3 m, is similar to the length of the vehicle, 4.5 m. The values of the electric field in the telephony bands, however, were attenuated by factors of between 0.54 and 0.66. In these cases, the wavelengths are an order of magnitude lower, 0.38 m for 800 MHz and 0.14 m for 2100 MHz.

With respect to the uncertainty associated with the measurements, this is also altered by the sampling design. As was seen in Section 3.2, the standard uncertainties of the individual 2-minute measurements with the vehicle stationary were greater than the calibration uncertainties provided by the manufacturer. The uncertainties associated with the vehicle when making four measurements at different angles were even greater, being 1.6 dB for the FM band and around 2.4–2.5 dB for the downlink telephony bands studied.

Table 4
Statistics of the exposure coefficients (EQ) in the city of Cáceres in the FM radio band and in the downlink mobile telephony bands. The values must be multiplied by 10^{-6}. EQ_{25}, EQ_{50}, EQ_{75}, and EQ_{95} are the 25th, 50th, 75th, and 95th percentiles, respectively. Sample size 3065.

	EQ_{avg}	σ	EQ_{min}	EQ_{25}	EQ_{50}	EQ_{75}	EQ_{95}	EQ_{max}
FM	145	403	0.13	8.6	28	100	632	7788
LTE 800	5.8	21	0.04	0.13	0.63	3	25	376
GSM + UMTS 900	32	225	0.05	1	4.1	15	100	8113
GSM1800	13	84	0.03	0.33	1.5	6	49	3754
UMTS2100	8.7	33	0.02	0.28	1.1	4.5	36	847
Total	205	502	0.47	20	59	176	856	9814

4.3. Comparison with the literature

Comparing our electric field values with the literature, we found that in some cases they are similar and in others they are different. The mean electric field values obtained in the present work were 0.231, 0.057, 0.140, 0.124, and 0.110 V/m for the FM, LTE 800(DL), GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL) frequency bands, respectively. In order to make comparisons with literature values, we also calculated the power density levels in these bands. These were 0.302, 0.024, 0.152, 0.119, and 0.085 mW/m^2, respectively.

The band with the greatest electric field values in our study was FM radio. The values were above those commonly published in the literature. Thus, for example, Estenberg and Augustsson (2014) report 0.047 mW/m^2 for this band in Sweden, Bhatt et al. (2016) 0.03 V/m in Australia and 0.05 V/m in Belgium, and Ibrani et al. (2016) 0.044 mW/m^2 in Kosovo. The fact that there are several locations with powerful FM radio antennas in the vicinity of the city of Cáceres is probably the cause of the relatively high electric field values that we registered.

Values greater than ours (0.687 V/m) were obtained in a recent study carried out by Koppel and Hardell (2022) in Columbia, USA. And, in an international context, Sagar et al. (2018) sampled 94 micro-environments of 6 countries (Switzerland, Ethiopia, Nepal, South Africa, Australia, United States of America) and obtained a wide range of electric field values (0.07–1.80 V/m).

With respect to the mobile telephony downlink bands, the exposure levels reported in the literature cover a wide range. For example, Urbinello et al. (2014) conducted an outdoor study of the cities of Basel and Amsterdam. They obtained values of 0.13 and 0.27 V/m for the GSM + UMTS 900(DL) band for these two cities, respectively. The respective values they obtained for the GSM 1800(DL) band were 0.19 and 0.30 V/m and for the UMTS 2100(DL) band 0.08 and 0.14 V/m in the two cities. These values are in line with those obtained in the present work.

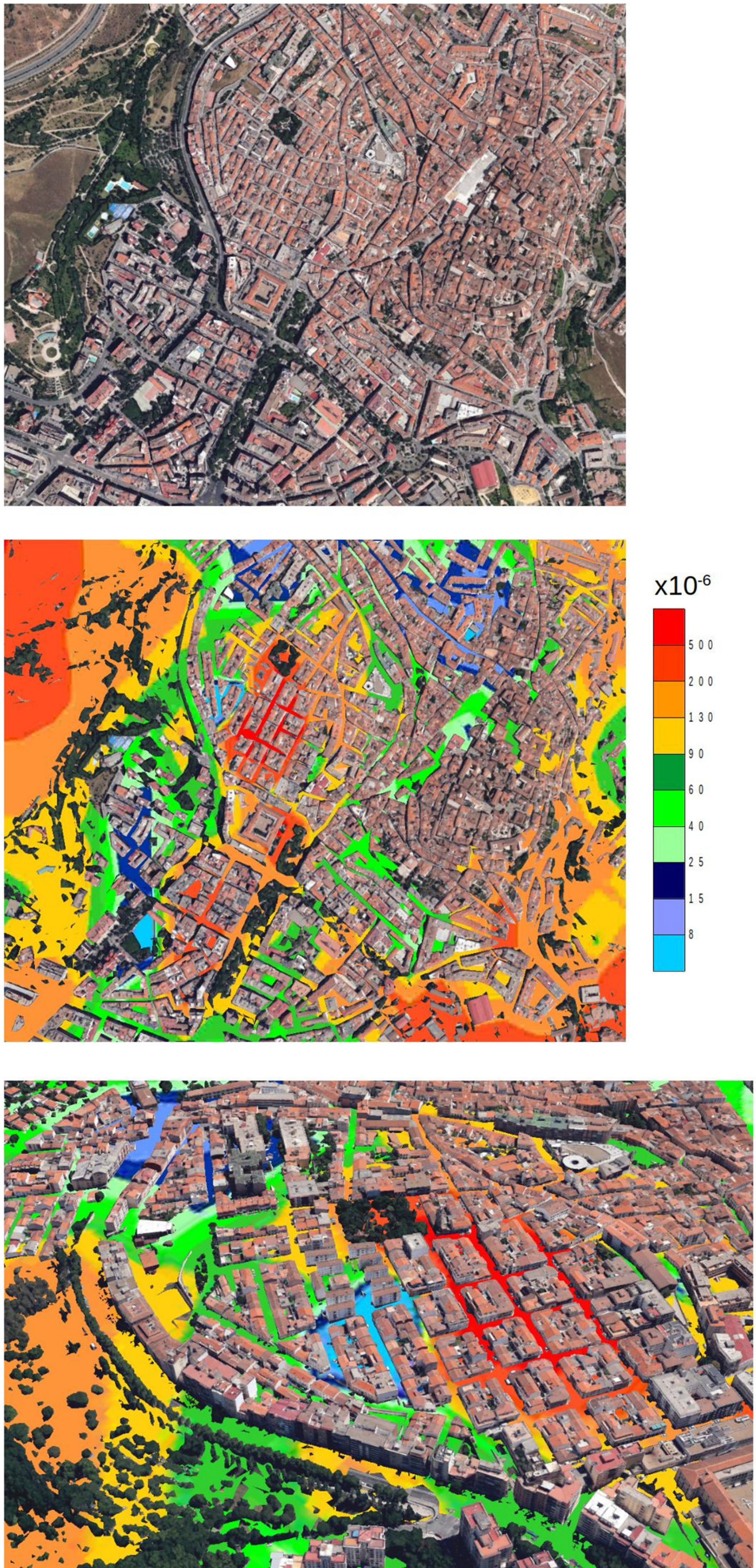

x10-6
500
200
130
90
60
40
25
15
8

Table 5
Summary of some studies of exposure to RF-EMF in the urban environment, including georeferencing of data and mapping.

Reference	City/surface/sampling points	Sampling	Main goal	Main findings
Azpurua and Dos Ramos (2010)	Caracas (Venezuela)/2.64 km^2/206	Broadband/Static	To compare three spatial interpolation techniques with the goal of determining which method creates the best representation of reality for measured electric field intensity.	Substantial difference between the estimating ability of the three interpolation methods and IDW performing better overall.
Aerts et al. (2013)	Ghent (Belgium)/1 km^2/650	Broadband/Static	To propose a new urban RF-EMF exposure assessment method that focuses on the detection and characterization of regions with elevated or high RF-EMF exposure.	Relatively fast construction of an accurate heat map of the outdoor exposure to RF-RMF that characterizes and outlines the hotspot regions, using kriging as interpolation technique.
Gonzalez-Rubio et al. (2016)	Albacete (Spain)/12,019	PEM/Moving (bicycle)	To prepare a lattice map of the exposure to RF-EMF emitted by mobile phone base stations.	Weak correlation between the location of the antennas and the exposure levels to RF-EMF.
Sánchez-Montero et al. (2017)	Alcalá de Henares (Spain)/35 km^2/78	Broadband/Static	To compare the EMF exposure levels in the city over a ten-year period.	A moderate increase from 2006 to 2010 and almost invariant from 2010 to 2015. Although the whole dataset does not have relevant statistical difference, they have found marked local differences.
Koppel and Hardell (2022)	Columbia (USA)/1517	PEM/Moving (walking)	To characterize the wireless infrastructure and public exposure to RF-EMF, including the sub-millimeter wave 5G.	The findings suggest that cell phone base station antennas should be distinct and noticeable, as this would assist individuals who need to limit their exposure by distancing themselves from RF sources.

Our data are also in line with those published by Bolte et al. (2016) for Cambridge and Amersfoort. They studied the GSM + UMTS 900(DL) and GSM 1800(DL) bands. For the first of these bands, the values were between 0.004 and 0.071 mW/m^2 in Cambridge and between 0.033 and 0.687 mW/m^2 in Amersfoort. For the second, the values were between 0.008 and 0.160 mW/m^2 in Cambridge and between 0.006 and 0.239 mW/m^2 in Amersfoort.

Our data for DL mobile telephony are within the published range of 0.18 to 1.58 V/m in the study conducted by Sagar et al. (2018) in the international context, but greater than those reported by Ramirez et al. (2019) in a study carried out in the city of Albacete (Spain) of 0.060 mW/m^2 for the DL mobile telephony bands of GSM + UMTS 900(DL), GSM 1800(DL), and UMTS 2100(DL).

In general, one observes that the published radio frequency levels fluctuate from one study to another, probably due to the different sampling protocols used and the number of micro-environments involved. Nonetheless, in most situations, the mean values remain within the same order of magnitude.

4.4. Exposure coefficients

A step further in measuring the radio frequency level, whether in units of electric field (V/m) or of power density (mW/m^2), is in the calculation of the exposure coefficients. Not all frequencies are equally dangerous since the human body acts as a resonant antenna for wavelengths similar to its length making the energy transfer maximal. For this reason, the regulatory reference levels are frequency dependent. The use of exposure coefficients allows all emissions to be considered together after weighting them by their reference levels. They therefore constitute a more accurate approximation of human exposure to radio frequencies.

In the present study, the mean value of the exposure coefficient, 205×10^{-6}, represents only 0.02 % (a factor of about 5000 times below) of the maximum value recommended by ICNIRP (1998). Some 95 % of the levels are below 0.1 % (about 1000 times), and the highest level is at just 1 % (about 100 times below).

That the greatest contribution to exposure comes from the FM radio band (66.3 %) is due to two factors. Firstly, its electric field levels are higher, as seen in the statistical data presented in Table 3. Secondly, the reference levels for the FM band are the most restrictive (28 V/m compared with, for example, the 61 V/m of the UMTS 2100 band), so that the same electric field has a greater effect on exposure.

There are few studies in the literature with which to compare exposure levels. In our previously mentioned work (Paniagua et al., 2020) which was carried out around 14 buildings in the city, we obtained exposure coefficients with a median value of 25×10^{-6} and a range of $9.1–678 \times 10^{-6}$. Both are below those presented in the statistical data of Table 4 because the entire city has now been sampled, including the peripheral neighbourhoods most exposed to FM radio antennas.

In another work carried out in the city of Mérida (Spain) (Paniagua et al., 2009), data were taken with a spectrum analyser at 18 points in the city's urban area corresponding to so-called sensitive spaces. A median of 16×10^{-6} and a range of $3–1060 \times 10^{-6}$ was obtained for the coefficient of exposure due to thermal effects. These therefore are also of the same order of magnitude as in the present work.

4.5. Advantages and limitations

In previous studies (see Table 5), the authors investigated radiofrequency (RF) exposure in urban areas for different purposes. For example, Azpurua and Dos Ramos (2010) compare three spatial interpolation techniques: Spline, IDW and kriging; Aerts et al. (2013) propose a new urban RF-EMF exposure assessment method that focuses on the detection and characterization of regions with elevated or high RF-EMF exposure; Gonzalez-Rubio et al. (2016) prepare a lattice map of the exposure to RF-EMF emitted by mobile phone base stations; Sánchez-Montero et al. (2017) compare the EMF exposure levels over a ten-year period, and Koppel and Hardell (2022) characterize the wireless infrastructure and public exposure to RF-EMF.

In this context, the main strengths of this work are the joint use of georeferenced data and electric field levels broken down by frequency bands, and a large number of measurement points (3065) collected in a wide urban area (11.88 km^2) using a rapid outdoor sampling technique. The data generated in this work can be compared with frequency-dependent reference levels of any regulation, current or future.

An advantage of the measurement points being georeferenced is that they make it easier for us to create graphic representations, using graduated symbols, like those in Fig. 8, and to know where the points with higher or lower RF levels are located. In addition, through interpolation techniques, continuous distributions can be created that can be easily merged with aerial images such as the one in Fig. 9. The availability of this spatial information is important when planning future more intensive sampling in areas of interest.

Fig. 9. Spatial distribution of the exposure coefficient for multiple-frequency sources in the city of Cáceres. The representations were obtained by merging the contour map generated by kriging and the Google Earth aerial image with the option “3D Buildings” activated. Top: Aerial image. Center: Contour map merged with aerial image. Bottom: Zoom-in on one of the city's neighbourhoods.

Another advantage of the protocol used in this study is that it is applicable to urban areas of other cities. It also allows the sampling to be replicated totally or partially in the future to study the temporal variation of the electric field levels.

This study has some drawbacks. Measurements were carried out homogeneously throughout the city, without focusing on any specific microenvironment or comparing exposure levels between different microenvironments, as is done in other studies (Urbinello et al., 2014; Sagar et al., 2018). This does not allow us to accurately assess human exposure to radio-frequencies since people spend most of their time outdoors in a city in specific places, such as parks, school playgrounds, shopping areas or residential yards. Future research might focus on the evaluation of exposure in these places taking the data provided in this study as a starting point.

Another limitation is that, due to the placement of the PEM inside the vehicle, the sampling technique alters the measurements and their associated uncertainties. The alteration of the measurements was corrected with the factors obtained in the experiment described in Section 3.2. On the other hand, the increased dispersion of the data requires a different management of uncertainty. Usually, in studies of compliance with regulations, *direct comparison* is used when uncertainty is low, i.e., comparing the measured level with the reference level. If, however, the uncertainty exceeds an established threshold, it is advisable to apply the so-called *additive approach* in which the uncertainty is added to the evaluation results before comparison with the reference level. As suggested by the European Committee for Electrotechnical Standardization (CENELEC) EN 50383 (EC, 2003) standard, the *additive approach* should be used in the case that the expanded uncertainty (1.96σ) (EC, 2008) exceeds 30 %. As seen in Table 2, the standard uncertainty in this study was between 20.9 % and 34.0 % for the different frequency bands considered. Hence, the expanded uncertainty clearly surpasses the 30 % value, and therefore the *additive approximation* must be used for comparison with the regulatory levels to take into account this increase in uncertainty due to the sampling device used.

A characteristic of this study and of other similar ones cited in the bibliography is that the measurement instrumentation captures radiation in limited ranges. In the case of PEMs such as ours, the frequency range is 87–5850 MHz, which includes the services addressed in Table 1. Although most of the electromagnetic radiation that affects people lies within this range, radiation from other important radio frequencies such as AM radio is not covered. The exposure coefficients for thermal effects of these radiations can be of the same order of magnitude as those found in the present work, and for electrical effects two orders of magnitude greater (Paniagua et al., 2009; Paniagua et al., 2010; Rufo et al., 2018). Although this type of study does not offer a complete vision of radio frequency exposure, it does allow exploration of a major part of the radio spectrum to which the population is exposed. It also allows one to analyse the temporal evolution of exposure to mobile telephony radiation, which changes more in the short and medium term due to the introduction of new generations, such as 5G, and the opening of new frequency bands.

5. Conclusions

The PEM–vehicle system allows rapid measurements of an important part of the radio spectrum in outdoor urban environments. This system alters the measurements and the uncertainty associated with them. The former was addressed by applying correction factors, and the latter by applying the *additive approach* to handling uncertainty. The electric field levels obtained in the present study are of the same order of magnitude as those commonly reported in the literature. The exposure coefficients represent at most 1 % of the maximum value recommended by ICNIRP. The use of a PEM with built-in GPS allows the measurements to be geo-referenced and quickly transported to a map or aerial photograph for better visualization and interpretation. The technique used in this work is scalable to cities of different sizes, and will allow measurements at different times in order to analyse the temporal variation of radio frequency levels.

CRediT authorship contribution statement

Jesús M. Paniagua-Sánchez: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Francisco J. García-Cobos:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Montaña Rufo-Pérez:** Methodology, Formal analysis, Resources, Writing – review & editing, Funding acquisition. **Antonio Jiménez-Barco:** Investigation, Resources, Writing – review & editing, Funding acquisition.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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