Brief Communication

Extensive Frequency Selective Measurements of Radiofrequency Fields in Outdoor Environments Performed with a Novel Mobile Monitoring System

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A novel, car based, measuring system for estimation of general public outdoor exposure to radiofrequency fields (RF) has been developed. The system enables fast, large area, isotropic spectral measurements with a bandwidth covering the frequency range of 30 MHz to 3 GHz. Measurements have shown that complete mapping of a town with 15000 inhabitants and a path length of 115 km is possible to perform within 1 day. The measured areas were chosen to represent typical rural, urban and city areas of Sweden. The data sets consist of more than 70000 measurements. All measurements were performed during the daytime. The median power density was 16 μW/m^2 in rural areas, 270 μW/m^2 in urban areas, and 2400 μW/m^2 in city areas. In urban and city areas, base stations for mobile phones were clearly the dominating sources of exposure. Bioelectromagnetics

Key words: exposure; power density; base stations; RF; spectral; radiofrequency fields

The general public is exposed to a wide range of radiofrequency (RF) fields from a variety of man-made sources. Measurements of human exposure to RF fields are performed due to various reasons, including: to test compliance with limits or guidelines [Alhekail et al., 2012], to classify individual exposure [Bolte and Eikelboom, 2012] or to evaluate exposure from a specific transmitter or technology [Henderson and Bangay, 2006]. These types of measurements are normally designed to find maximum exposure levels or to reflect exposure of specific groups or individuals. This article presents a novel mobile measuring system and a summary of the extensive data gathered with this system.

The measuring system, developed by the Swedish Radiation Safety Authority, is a car-based system that enables fast, large area, isotropic spectral estimation of the general public outdoor exposure to RF fields covering the frequency range of 30 MHz to 3 GHz. This frequency range includes the most significant sources of RF exposure to the general public and the measurements can be used to identify and evaluate exposure trends in outdoor environments in the long term. Even though the exposure of the general public is known to be well below established guidelines, monitoring of long-term exposure trends is important from an environmental assessment point of view. The results can also be the basis for a sound risk communication with the general public.

All measurements were performed in 2012 during the daytime (08:00 a.m.–6:30 p.m.). The measured areas were chosen to represent typical rural, urban, and city areas of Sweden. The locations of the measurements are described in Table 1. Using the system described in this article, we have found that it is possible to completely map a small town (Ljungby) with 15000 inhabitants in a single day. We drove at a speed of 6 m/second on average and the total path length was 115 km. In this study, Ljungby was the only completely covered area. For the other data sets, each area was only covered partly, meaning that not all streets and roads were driven through. Measurements

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TABLE 1. Measured Power Densities and Route Information for the Different Data Sets

Type of area	Rural	Urban	Capital city	City
Locations	Ryssby, Ekerö	Göteborg, Helsingborg, Jönköping, Ljungby	Stockholm	Solna[a]
Population density[b] (inhabitants/km^2)	117–645	1029–2640	4825	4700
Total driving distance (km)	121.4	250.4	41.3	17.9/17.9/18.0[a]
Total driving time (hh:mm)	05:45	12:13	02:53	00:55/00:54/00:52[a]
Number of measurements	17323	42285	10724	2345/2316/2234[a]
Median[c] (μW/m^2)	16	270	2600	1600/1670/1409[a]
Arithmetic mean[c] (μW/m^2)	230	1500	6700	3100/3278/3208[a]
FM-radio[d] (87.5–108 MHz)	1.1	47	13	9.3/12/12[a]
DAB and DVB-T[d] (174–240, 470–790, 1452–1480 MHz)	8.1	30	53	8.4/10/10[a]
Tetra[d] (380–385, 390–395 MHz)	3.0	5.4	6.0	7.6/5.3/3.7[a]
LTE[d] (791–821, 832–861 MHz)	39	270	1300	600/730/620[a]
GSM and UMTS uplink[d] (876–915, 1710–1785, 1900–1980 MHz)	0.23	0.78	1.1	0.27/0.82/0.27[a]
GSM and UMTS downlink[d] (921–960, 1805–1880, 2110–2170 MHz)	200	1200	5400	2400/2500/2600[a]
DECT[d] (1880–1900 MHz)	0.0053	0.13	0.13	0.035/0.091/0.051[a]
WLAN[d] (2400–2484 MHz)	0.0097	0.72	0.19	0.068/0.064/0.024[a]
Other transmitters[d] (within 30 MHz–3 GHz)	0.78	5.4	29	9.4/2.9/1.9[a]

[a]The same route was measured three times within 2 days.
[b]Data from SCB (Statistics Sweden) 2010.
[c]For integrated power densities (30 MHz–3 GHz).
[d]Arithmetic mean (μW/m^2).

were performed in both residential, industry and inner city areas. In a few occasions, some parts had to be driven twice in the same route due to the design of the road network. These double measurements, as well as measurements from standing still, for example at traffic lights, have not been excluded in the analysis. About 10–20% of all measurements were made standing still. The fact that the average driving speed was lower in inner city areas than in the outskirts means that the sample rate per meter was higher for inner city areas. Assuming that the field strength is higher in inner city areas than in the outskirts, this would lead to overestimation of average exposure within the measured area.

There is no standard or existing solution for how these kinds of mobile measurements should be carried out. The system described in this article is based on existing commercial components: a spectrum analyzer (FSL 6; Rohde and Schwarz, Munich, Germany) and a three-axis measuring antenna (Satimo 30 MHz–3 GHz; Rohde and Schwarz). The antenna was mounted at 2.4 m above the ground, on a non-conducting wooden stand fixed in an open roof box that was placed on a car (Volvo V70 II). The bottom of the roof box was filled with RF absorbers (APM 20; Siepel SAS RCS, La Trinité sur Mer, France) to avoid interference from RF reflections from the car's roof. The measuring antenna was connected to the spectrum analyzer with a low-loss coaxial cable.

The settings of the spectrum analyzer affect the performance of the system. The chosen settings are a trade-off between sensitivity, accuracy, and quantity. For the measurements presented in this article, single sweeps with RMS detector was used. The resolution bandwidth was set to 1 MHz and the video bandwidth was set to 10 MHz. These settings gave us the possibility to measure a complete and isotropic power density spectrum, tagged with its global positioning system coordinates (GPS), once every second. The actual total measuring time was 370 milliseconds per measurement; the rest of the seconds was used for data transfer and computation.

The sensitivity of the measuring antenna is frequency dependent and the detection limit of the spectrum analyzer depends on the settings. Figure 1 presents the frequency-dependent detection limit of the measuring system, using the spectrum analyzer settings described above. Figure 1 also shows how the detection limit is improved when using the internal preamplifier of the spectrum analyzer. The preamplifier could, however, not be used in urban and city areas since the power densities would cause saturation.

The antenna consists of three separate orthogonal antenna elements, one for each polarization. One

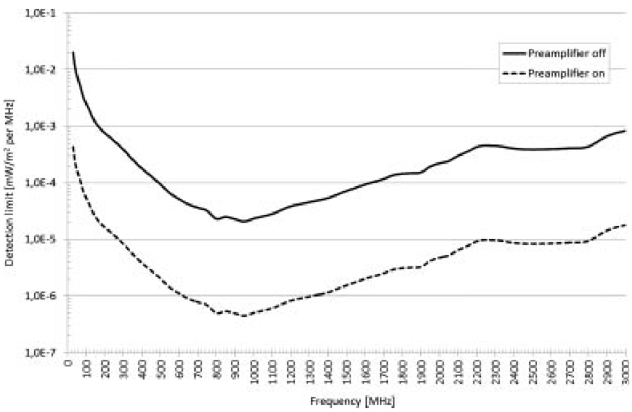

Fig. 1. Detection limit of the measuring system with and without preamplifier.

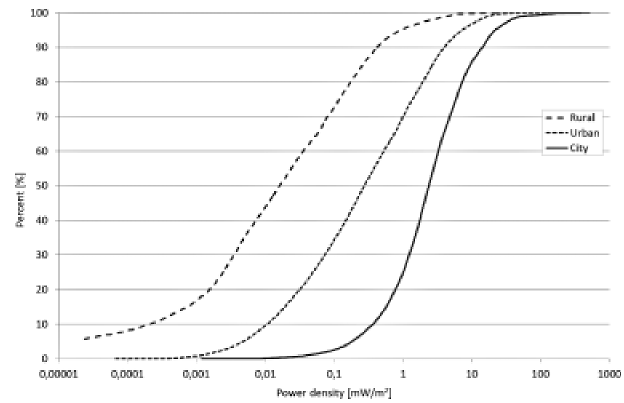

Fig. 2. Cumulative distribution functions for the measured areas, specified in Table 1. The measurements from Stockholm are included in "city." For rural areas, 5.7% of the measurements gave non-detectable values since the power densities were below the detection limit of the measuring system, specified in Figure 1.

single frequency spectrum is measured and saved for each polarization. When analyzing the spectra, frequency-dependent threshold levels are set just above the maximum random noise floor of the spectrum analyzer to prevent noise from affecting the analysis. Calibration factors are then added and a combined spectrum is computed from the three single spectra and the total power density of the combined spectrum is instantaneously presented on a screen.

The spectrum analyzer and antenna switch is controlled by a computer, which also stores the time of the measurement, the GPS coordinates and the spectral RF data. The GPS coordinates are used to plot the driving route in a map. The measurements make it possible to find hotspots in real time and to later analyze frequency components. The measurements are frequency selective and it is therefore possible to distinguish different sources, for example: uplink, downlink, specific service providers, etc.

The results for rural, urban, and city areas are presented in Table 1. In urban and city areas, base stations for mobile phones were clearly the dominating sources of exposure. The cumulative distribution functions for the separate areas are shown in Figure 2 and it is clear that both higher levels and a narrower range of power densities are observed as the population density increases. All presented power densities are vector sums of the three measured polarizations.

The results are likely to be valid also for other countries since similar communications infrastructures exist in most other countries. The measured power densities in this study align with a number of other studies in different countries that estimated the mean exposure of 173323 measurements worldwide to be 0.73 mW/m^2 [Rowley and Joyner, 2012]. The comparison is, however, not straight forward since those measurements do not cover exactly the same time periods and frequency ranges and the measurement methods are not clearly described.

There are many factors that affect the measurement result. One of the most crucial factors is the variation of the actual field strength over time. The variation is caused by sporadic, pulsed or moving transmitters or by multipath fading due to reflections from moving objects. A single measurement of the field strength from transmitters like the global system for mobile communication (GSM) base stations can be both under- and overestimated depending on whether the burst is caught by the measurement. However, the extensive amount of measurements in each data set ensures that the median or mean power density within a measured district is robust. The repeatability of the measurement method and its possibility to find local hotspots is good. This has been confirmed by a test where the same route has been measured three times (see the Solna measurements in Table 1).

Another factor that affects the accuracy of a single measurement is the fact that the three different polarizations are not measured concurrently, but one at a time and then combined. The total measuring time for all three polarizations is 370 milliseconds, which corresponds to 3 m at a speed of 30 km/hour. The measurement speed is limited to 30 km/hour, meaning that the measurements are not single spot measurements, but rather means of distances of up to 3 m. For a deeper analysis of the statistical distribution of the field strength within a measured distance [see Lee, 1985].

Measurements have been carried out in order to investigate if speed affects the results when measuring field strength from a single continuous wave (CW) transmitter. During this test, the transmitter was set to three different frequencies: 862.5, 2015, and 2484 MHz, respectively, for both vertical and horizontal polarization. The car was driving at four different speeds: 0, 10, 20, and 30 km/hour, respectively. The car was driven both towards and perpendicular to the bore sight of the transmitting antenna. The mean deviation from stationary was less than 0.5 dB (-11% to $+12\%$) for all speeds, frequencies, and polarizations, suggesting that speed did not affect the result of this specific measurement.

The errors described above are random errors that would cancel out when studying the median or mean for a large set of data, while the systematic errors are related to the calibration and structure of the measuring system. The antenna, antenna cable, and spectrum analyzer were calibrated by the manufacturers. The uncertainty was <1 dB (-21% to $+26\%$) for the antenna and <0.5 dB (-11% to $+12\%$) for the spectrum analyzer. The isotropy of the measuring antenna was specified to be <2 dB (-37% to $+58\%$). Reflections from the roof of the car will however change the characteristics of the antenna. This impact has been reduced by minimizing reflections from the roof of the car by adding RF absorbers, as described above.

The total system, with the antenna mounted on the car, was calibrated at the national body for verification of measuring instruments (SP Technical Research Institute of Sweden, Borås, Sweden). The correction factors (horizontal antenna diagram) were measured at three different CW frequencies: 862.5, 2015, and 2484 MHz, respectively, with both vertical and horizontal polarization. The mean of the correction factors is a good characterization of the system since the car is moving randomly in relation to the transmitters during the real measurements. The mean of the correction factors was within -3.6 to 0.76 dB (-56% to $+19\%$) for all measured frequencies and polarizations, indicating that the car only has a slight impact on the accuracy of the measurements.

The height of the measuring antenna was 2.4 m, which is somewhat higher than for normal exposure measurements. This would likely lead to an overestimation of exposure from higher localized transmitters such as base stations while exposure from transmitters near the ground, for example mobile phones and Terrestrial Trunked Radio (TETRA) handsets, can be slightly underestimated. In an article by Kim et al. [2012], the expanded uncertainty for evaluating human exposure levels to RF fields from base stations was estimated to 3.82 dB (-58.5% to $+141\%$).

Detailed analysis of our data shows that the integrated measured power density of 30 MHz–3 GHz can vary by a factor of >50 dB (10000000%) over a driving distance of 10 km. In addition, a single measurement has limitations in accuracy due to continuous data acquisition during movement. The output data have, therefore, mainly been used to compute average exposure for larger areas. Even though each single measurement is associated with uncertainties, the large number of measurements in both urban and rural areas in Sweden provides a solid basis that allows detailed statistical analysis of the exposure of the general public to RF fields.

REFERENCES

Alhekail ZO, Hadi MA, Alkanhal MA. 2012. Public safety assessment of electromagnetic radiation exposure from mobile base stations. J Radiol Prot 32:325–337.

Bolte JFB, 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.

Henderson SI, Bangay MJ. 2006. Survey of RF exposure levels from mobile telephone base stations in Australia. Bioelectromagnetics 27:73–76.

Kim BC, Yun JH, Park SO. 2012. Uncertainty estimation for evaluating human exposure levels to RF electromagnetic fields from cellular base stations. IEEE Trans Electromagn Compat 54:246–253.

Lee WCY. 1985. Estimate of local average power of a mobile radio signal. IEEE Trans Veh Technol 34:22–27.

Rowley JT, Joyner KH. 2012. Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations. J Expo Sci Environ Epidemiol 22:304–315.