DRONE BASED MEASUREMENT SYSTEM FOR RADIOFREQUENCY EXPOSURE ASSESSMENT

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Abstract- For the first time, a method to assess radiofrequency (RF) electromagnetic field (EMF) exposure of the general public in real environments with a true free-space antenna system is presented. Using light weight electronics and multiple antennas placed on a drone, it is possible to perform exposure measurements. This technique will enable researchers to measure three dimensional (3D) RF-EMF exposure patterns accurately in the future and at locations that currently are difficult to access. A measurement procedure and appropriate measurement settings have been developed. As an application, outdoor measurements are performed as a function of height up to 60 m for Global System for Mobile Communications (GSM) 900 MHz base station exposure.

The research agenda of World Health Organization (WHO) lists the need to characterize radiofrequency (RF) electromagnetic field (RF-EMF) emissions and assess exposure levels [WHO, 2010]. Various experimental methods have been proposed to assess RF-EMF exposure; measurements are performed using spectrum analyzers (spot measurements at dedicated locations), exposimeters (large sampling, worn on body), or using a car based-measurement system. These data have been used for compliance testing, epidemiological studies, and to construct exposure heat maps [Aerts et al., 2013].

Spatial EMF strength measurements using accurate spectral equipment and required measurement procedures have been investigated in literature [Bornkessel et al. 2007; Joseph et al. 2009, 2010, 2012]. A standard of the European Committee for Electrotechnical Standardisation (CENELEC) has been developed for the in-situ EMF measurements [CENELEC, 2008], which explicitly requires a fully isotropic antenna. However, theoretically and practically, it is impossible to create such an antenna, which is physically supported or connected with a cable. This is associated with additional measurement uncertainties or, even worse, consistent offsets in the measurements. These measurements are time consuming but accurate and have the advantage to be suitable for compliance evaluation with international guidelines such as e.g., ICNIRP [1998].

RF-EMF exposure assessment studies using exposimeters, mostly worn on the body and investigating spatial and temporal field aspects, enable one to perform exposure measurements with more spatial samples. However, this comes at a cost of having less accuracy and more measurement uncertainty due to the influence of the human body [Joseph et al. 2008; Frei et al. 2009; Bolte et al. 2012; Thielens et al. 2013]. These uncertainties are not suitable for compliance evaluation but enable us to determine average exposure levels for e.g., epidemiological studies.

The system of Estenberg and Augustsson [2013] is a car based, measuring system for estimation of general public, outdoor RF exposure. A broad frequency band (30 MHz to 3 GHz) has been targeted in Estenberg and Augustsson [2013] with the purpose of performing measurements over large areas (e.g., a town) and providing average exposure values over these areas (no compliance assessment). Bolte et al. [2015] developed a car mounted mobile measurement system, usable to assess average exposure values in certain areas as well. However, these systems suffer from antenna anisotropies of the car-antenna system due to either reflection of the vehicle or alternatively shielding by the vehicle.

None of the existing methods proposed until now allow for true isotropic, free-space RF EMF measurements. Moreover, none of the aforementioned methods enable one to measure RF EMFs at different heights and locations that are difficult to reach by the operator executing the measurements (e.g., carrying expensive and heavy spectral equipment in front of a base station antenna mounted on a pole or performing measurements as a function of height outdoor or indoor for large shopping centers or industrial halls). Another drawback of the aforementioned methods is that these methods do not allow to sample data in a quick way without operators carrying exposimeters and influencing the measurements by their presence. Therefore, we propose, for the first time, a drone-based measurement system for isotropic estimation of three dimensional (3D) RF-EMF exposure.

Our goal is to assess RF-EMF exposure with a triaxial drone-system in an accurate way, using a high sampling measurement procedure in order to obtain similar accuracy as spectrum analyzer spot measurements. As an application, electric-field measurements in the Global System for Mobile Communications (GSM900) downlink (DL) band around 950 MHz are performed from

1 to 60 m in a suburban office environment. To the authors' best knowledge, we present the first drone-system for RF-EMF exposure measurements, which enables us to characterize, for the first time, the exposure pattern as a function of height up to 60 m above ground level.

The novel measurement system consists of the drone self, three identical nodes consisting of lightweight electronics, and 3 orthogonal lightweight monopoles or alternatively 3 linearly polarized planar patch antennas calibrated in an anechoic room.

The drone is a hexacopter constructed from the DJI F550 flamewheel kit (DJI, Shenzhen, China), consisting of 6 motor arms and a main printed circuit board (PCB) for feeding the 6 motor arms (Fig. 1a). The hexacopter uses 2 types of motors (3 wounded for clockwise rotation and 3 wounded for counter clockwise rotation). To control the hexacopter, a controller from DJI (type NAZA V 2) is used. The transmitter and receiver for wireless drone control (using 2.4 GHz T-FHSS Frequency Hopping Spread Spectrum) are of type Futaba T10J and R3008SB (Futaba, Champaign, IL), respectively. These do not interfere with the measurements in the GSM900 DL band. Lithium polymer (LiPo) batteries (PK racing, Dordrecht, The Netherlands) are used to feed the drone system. The hexacopter has a Global positioning system (GPS) (for positioning and autonomous flight mode), an altitude meter (barometric pressure altimeter), and a compass.

The RF exposure acquisition system consists of three lightweight and compact nodes, which is important to minimize the impact on the battery consumption and thereby obtaining maximum flight time. These nodes contain a commercially available log detector (ADL5513, 30 grams, Analog devices, Norwood, MA), which is connected to a small monopole antenna (see further) via a tuned GSM downlink 942.5 MHz SAW filter (TRIQUINT 855820, 20 grams, Hillsboro,

OR). The log detector output is connected to a 14 bit analog digital convertor, which is controlled via I2C by a microcontroller (ATMEGA328, 28 grams, Atmel, San Jose, CA). The collected data is stored on a Secure Digital (SD) card accessed by the microcontroller. The data can be transferred to a personal computer after completion of the measurements.

Three identical lightweight antennas are connected to the three acquisition units. The antennas are positioned below the drone self (Fig. 1a) on a plastic holder according to three orthogonal axes (nodes A, B, and C) in order to be able to calculate the total electric-field strength. Axis A is orthogonal to the ground plane, while axes B and C are orthogonal to each other and both in the same plane. Monopole antennas of type ANT-GXH615 (20 grams, Round Solutions, Neu-Isenburg, Germany) are used (bandwidth 824 – 960 MHz and 1710 - 1990 MHz, gain 2.14 dBi) or the planar antennas presented in Thielens et al. [2013] and Vanveerdeghem et al. [2015] (bandwidth 60 MHz, gain 3 dBi). These antennas are designed for the GSM900 DL frequency band with a reflection parameter S_{11} lower than -10 dB in the full GSM DL band and both types are lightweight and suitable for the presented application. As the antennas are placed below the drone, consisting mainly of plastic material, the influence of the drone is limited. In future studies a full calibration with the drone and antenna system in an anechoic will be performed. In this study, we assume a limited influence of the drone.

The uncertainty of the system is determined accounting for the uncertainty analysis components listed in CENELEC [2008] and Thielens [2015]. Table 1 lists the components and the uncertainty budget. The combined uncertainty is 2.3 dB, which is lower than other systems, when applying this full uncertainty analysis. Uncertainty terms [Thielens, 2015] related to the anisotropy of the antenna caused by the body of an operator or mounting on a carrier (a vehicle for example), are avoided thanks to the drone measurement system which operates in free space.

As an application, measurements are performed from 1 to 60 m above ground level. The area is a suburban office environment (Fig. 1b). The following measurement procedure and settings are proposed. First, the drone is calibrated with the antennas and electronics connected for flight stability reasons. Second, a short test flight is performed in order to account for e.g., different influence of the wind when being higher or other weather conditions. Third, the actual flights are performed. The sampling of the nodes is 1 Hz and the root-mean-square (RMS) electric field (and power) is measured over each sampling period. Measurements as a function of height are performed and over each 3 m median values over 30 s are calculated (in Joseph et al. [2010] the signal is also measured over 30 s. This measurement period is used until the GSM signal stabilizes). The height is logged using an altitude meter (depends on the weather conditions because this is based on barometric pressure).

Three nodes have thus been used (denoted as node A, B, C, Fig. 1a). Figure 2 shows the measurements of the three orthogonal components and the total electric-field strength as a function of the height. All measured field values up to 60 m satisfy the International Commission on Non-ionizing Radiation Protection (ICNIRP) guidelines [ICNIRP, 1998]. The maximal field value in the GSM900 DL band equals 0.52 V/m (0.73 mW/m^2), which is 81 times (6559 for power densities) below the ICNIRP reference levels for the general public. Field values increase with height up to about 24 m to 30 m, where the highest values of about 0.5 V/m occur. This can be explained by the fact that the measured exposure is due GSM mobile phone base stations, typically installed at a height of 30 m (the nearest base stations have heights of 25, 30, and 33 m). These base stations have directive antennas with a tilt of typically 0 to 6°. Thus, the highest exposure does not occur at ground level, but within the main beam at a height

of 20-30 m. Above 30 meters, the field values in Figure 2 decrease again, as these positions are above the main beam of the base station antennas.

The strengths of this study are the following. This is an accurate system that will enable to construct 3D exposure maps, fast sampling, and characterization of exposure as a function of height. It is easily extendable to other frequency bands. Moreover, it is a triaxial, isotropic measurement system that does not suffer from any shielding effects. Limitations are the weather conditions: when there is too much wind, the drone is difficult to stabilize (accurate wind predictions are possible), and no rain is preferred. Further limitations are that the operator has to be trained to perform flights with a drone. One could argue that automatic flights are possible, but this will not be allowed by future (national) legislation and a flight license will be needed. Moreover, batteries last typically 15-20 min, depending on the carried weight. This is countered in our study by using lightweight RF nodes. So different flights are needed to collect an extensive data set. For the presented application up to 60 m, 3 batteries (3 takeoffs in Figure 1b) were needed to perform the measurements. By continuously monitoring the height with the altitude meter and position using GPS, it is possible to realize measurement campaigns consisting of several flights. Moreover, the quality of LiPo batteries improves each year.

To summarize, for the first time, a triaxial drone based measurement system for RF-EMF exposure is presented and for the first time the RF exposure pattern as a function of height up to 60 m is characterized. The highest measured exposure of 0.52 V/m occurs at 24 m and is 81 times below the ICNIRP reference levels for the general public. The proposed drone measurement system will enable us to assess experimentally 3D RF-EMF exposure in real environments.

The use of 3D radiowave propagation models gains a lot of attention among epidemiologists [Breckenkamp et al. 2008; Bürgi et al. 2010; Beekhuizen et al. 2013; Martens et al. 2015]. They use detailed information about antenna location and radiation patterns, 3D building data and topography to compute the field strength of the downlink sources of different frequencies. In this way 3D exposure heat maps are constructed and used in epidemiological studies. The drone system can serve as input and validation to such 3D exposure models.

Future research will consist of extending the system to other frequency bands and of constructing 3D exposure heat maps, accounting for height (extension of current 2D exposure heat maps). Also exposure investigation for occupational circumstances, in large halls and at places that are difficult to reach will be part of future work. Finally, the measurement system has the potential for environmental monitoring by collecting measurements continuously for a trajectory.

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TABLE 1: Uncertainty Assessment of the System in the GSM 900 DL Band.

Figure 1: (a) Picture of the drone with indication of three nodes and axes. The nodes consist of lightweight electronics and antennas. (b) 3D view of the office environment and the flight trajectories (three takeoffs).

Figure 2: Electric-field strength of GSM900 DL signal in V/m as a function of height up to 60 m.