

Article

Investigation on Electromagnetic Immunity of Unmanned Aerial Vehicles in Electromagnetic Environment

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Abstract

The increasing complexity of the electromagnetic environment poses an increasing risk to unmanned aerial vehicles (UAVs) operating in airspaces subject to adverse electromagnetic effects. This paper investigates the potential electromagnetic interference that UAVs may encounter during flight through the lens of electromagnetic compatibility (EMC), which defines the requirements for the proper operation of UAV electronics. According to existing EMC standards, the immunity threshold for typical commercial drones is 10 V/m. However, European standards for public exposure permit electromagnetic fields and suggest that it is possible for an electromagnetic field of a mobile base station antenna to be as strong as 61 V/m. To assess drone vulnerability to its electromagnetic environment, investigation was conducted in an anechoic chamber, which determined that commercially available drones typically experience uncontrolled descent when subjected to an electric field strength of 30 V/m or higher. The primary coupling path for this interference is through the UAV's internal cables, as induced parasitic currents perturb the motor control signals. This disruption leads to flight instability as the propellers can no longer be reliably controlled, resulting in flight instabilities. Based on a maximum effective radiated power (ERP) of 40 dBW per sector for a base station antenna, a minimum safe operating distance of 20 m was calculated. Adherence to this safe distance is therefore strongly recommended for any commercial drone operator to avoid EMI-induced flight failure.

Keywords: unmanned aerial vehicle; electromagnetic compatibility; electromagnetic interference; flight safety; trajectory planning

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1. Introduction

The rapid development of unmanned aerial vehicles (UAVs), commonly known as drones, has created new alternatives for both individual and professional applications. A key feature of these transport platforms is their ability to conduct flight operations without any crew on board. The term UAV is used generally for unmanned aircraft, which includes remotely piloted vehicles and autonomously flying drones. Although this term can also encompass a wide variety of land-based autonomous vehicles and even seafaring submarines, the demand for broad-range drone applications is projected to increase in the coming years. Due to their versatility, UAVs have a broad range of applications, from recreational use to critical commercial and military operations. When equipped with cameras or other sensors, they serve as versatile mobile platforms for various tasks, such as package delivery, surveillance, border control, and support for emergency response teams like fire brigades and police. They are also increasingly employed for environmental and

agricultural purposes such as forest monitoring, precision farming, and geodetic surveys. In other cases, UAVs can provide effective public services by monitoring traffic and air pollution and assisting in firefighting and rescue operations. They are also finding use in recreational hobbies, such as gaming, and aerial photography. However, the increasing popularity of UAVs in both military and civilian fields has raised a critical issue—the need to ensure their operational viability in complex electromagnetic environments.

Electromagnetic compatibility (EMC) standards mandate that all electronic devices must be resistant to a certain level of electromagnetic radiation [1,2] to ensure proper operation. These standards are meant to guarantee that electronic products will function correctly as long as the incident electromagnetic field strength remains below a specified threshold. Specific EMC immunity thresholds are delineated for distinct device categories, with the EMC immunity threshold for typical commercial drones being set at 10 V/m. This level of immunity might be insufficient in certain environments, where electric field strength can exceed this limit, particularly in the vicinity of cellular base station antennas or airport surveillance radars, which may pose a risk to the UAV and the environment in which it operates.

A conventional UAV is constructed with a non-metallic housing that serves as the structural backbone for its electronic components and propellers. As a complex electronic device, the UAV relies on an Internal Measurement Unit (IMU) that incorporates essential sensors, including an accelerometer, a gyroscope, a barometer, a compass, and a GPS module. Given their increasing use, European Union regulations mandate that UAV operations must meet safety standards equivalent to those in manned aviation [3]. This requirement for safe flight is intended to guarantee public security, particularly when UAVs are operated over gatherings of people and near critical infrastructure.

The vulnerability of UAV electronics to elevated electromagnetic field levels remains an important concern. Exposure to high-intensity fields can disrupt critical electronic systems, potentially leading to erratic flight behavior or an uncontrolled descent with severe consequences. Kang et al. documented a significant number of incidents in the United States caused by the uncontrolled fall of UAVs [4], highlighting the widespread impact on various industries.

Electromagnetic interference that leads to uncontrolled flight or accidents can occur when a UAV operates in the vicinity of base station antennas, where the electromagnetic field is particularly strong. While a complex electromagnetic environment is known to negatively affect the UAV's communication with its operator, a study by Zhao et al. has also demonstrated that, in such environments, the drone's internal cabling becomes a primary coupling path for electromagnetic energy. These cables connect the flight control system, the electronic speed control (ESC) board, and the motors [5].

In many popular drone models, these cables are not shielded, making them susceptible to incident electric fields that induce additional current. The level of this induced current depends on the orientation of the wires relative to the incident electric field vector. The induced current level can differ in each propeller cable, leading to asynchronous motor power delivery, which in turn disrupts flight stability, causing erratic behavior or even an uncontrolled fall. The amount of induced spurious current also depends on the relationship between the wire lengths (determined by the drone's physical dimensions) and EM field frequency.

On the other hand, Backstrom et al. revealed that susceptibility is lower at higher frequencies, a phenomenon explained by the fact that field-to-cable coupling decreases with the square of the wavelength [6]. In the case of pulsed radiation, it was shown that initial EM plays the primary role in causing an uncontrolled descent, and there is no conclusive

evidence to suggest that the damaging effect on a UAV can also be related to the pulse repetition frequency or pulse width.

Nevertheless, the required level of electromagnetic immunity for electronic devices is substantially lower than the permissible exposure levels established to protect people against electromagnetic radiation. This is because the so-called biological electromagnetic compatibility differs from the electronic EMC. The electromagnetic radiation exposure threshold for human safety is based on limiting thermal effects and the currents induced inside the body, criteria that do not directly apply to electronic hardware.

This work presents an investigation into the vulnerability of commercially available drones to electromagnetic fields equivalent to those emitted by base station antennas. This study demonstrates that the EM field strength from base station downlinks can exceed a UAV's immunity threshold in close proximity to the antennas, creating a significant risk of uncontrolled flight.

2. Investigation of UAV Damage Mechanisms in Strong Electromagnetic Field

The continuous miniaturization and functional integration of UAV electronics increase their susceptibility to electromagnetic interference, which poses a significant risk for operational safety and flight stability. The nature of the interference and the extent of its impact are determined by key characteristics of the electromagnetic field, including its electric field strength, carrier frequency, polarization, and modulation type.

Microwave field incidents on a drone can disturb communication with the operator or induce parasitic currents that influence internal electronic subsystems, such as the flight controller, navigation receivers, and other vulnerable components. A UAV's primary electronic systems typically include a datalink, a navigation system, a flight control system, electronic speed controllers, and motors [7]. The state of the wireless channel is critical for reliable radio communication.

Qiao et al. demonstrated that the receiver and the electronic speed controller are particularly vulnerable components [8]. The effects of field strength and pulse repetition frequency on the probability of damage were investigated by Zhang et al. [9–11]. Electromagnetic interference can also have a destructive effect on the datalink system [12,13]. This system is a two-way data transfer channel between the drone and the ground operator. It is a crucial system that facilitates wireless communication, with a data uplink for transmitting remote control signals and a data downlink for relaying the UAV's status.

The antenna in the datalink system can also serve as a potential gateway for electromagnetic energy to enter the internal circuitry. In the case of a narrowband incident signal whose frequency falls within the datalink's operating band, the interfering signal can reach the RF front-end through the "front-door" coupling pathway, potentially resulting in physical damage to sensitive devices. If the incident signal's frequency is outside the antenna's operating band, "back-door" coupling becomes the main pathway, which can lead to abnormalities in the datalink equipment power supply.

Sakharov et al. investigated the effects of pulse-modulated EM fields on the datalink system [14]. They found that the pulse repetition frequency and field magnitude can lead to the failure of the datalink between the remote control and the UAV. Malik et al. investigated radiofrequency interference from advanced technologies, such as 5G and GNSS, on aviation systems, focusing on the safety risk to communication systems [15]. Similarly, Li et al. tested the susceptibility of small UAVs to environmental radiofrequency energy emitted by nearby electronic systems, such as Wi-Fi hotspots and cellphones [16].

The flight control and navigation systems can be vulnerable to incident microwave radiation, which may result in abnormal operation [9–11,17,18]. These systems integrate

various sensors to measure the UAV's three-axis attitude angles and motion parameters, typically comprising an inertial measurement unit (IMU), an onboard microcomputer, and a GPS receiver. The onboard microcomputer is responsible for collecting and processing signals from these sensors to ensure stable flight, an accurate directional reference, and precise positional coordinates. Incident electromagnetic fields can interfere with sensors such as gyroscopes and magnetic compasses, leading to inaccurate attitude estimations. Furthermore, GPS receivers must capture satellite signals that are inherently low-power due to the long transmission distance. To receive these weak signals, the receiver requires high sensitivity, which in turn diminishes its ability to resist electromagnetic interference.

In some experiments, high-intensity fields are intentionally used to disable or destroy UAV electronics. The effects of strong microwave pulses, which can lead to component damage and flight failure, have been widely investigated. These strong, pulse-modulated signals are known as High-Power Microwaves (HPMs). Such investigations typically test the influence of several key EM field parameters, i.e., electric field strength, frequency, polarization, modulation, and duration of exposure. In some cases, these investigations aimed to determine the effects of these fields on the vulnerable UAV components. For example, Zhao et al. focused on HPM irradiation tests performed on a UAV under simulated flight conditions [19]. They found that, when the electric field strength reached 7.5 kV/m, the exposure disrupted normal electronic functions and caused the onboard microcomputer to crash.

Nevertheless, energy coupling from the electromagnetic field via internal cabling is a significant interference mechanism that can occur even in environments with electric field strengths lower than those of HPMs [9–11]. In this scenario, the induced currents do not directly damage the electronics; instead, the flight failure is caused by the resulting non-synchronous operation of the rotors. Any damage to the electronics is then a secondary effect, resulting from the physical impact of the fall.

This work experimentally investigated interference affecting the cables connecting the flight control system, the electronic speed control (ESC) board, and the motors. The internal cabling of the drone is shown in Figure 1.



Figure 1. View of drone cables.

Using injection tests, Zhao et al. analyzed the voltages coupled to the cables of a UAV [5]. They observed that the interference effects varied depending on the carrier frequencies of the injected signals. The specific carrier frequency of microwaves that can disturb the UAV depends on the length and structure of the cables in the UAV. The authors pointed out that the strongest coupling effect occurs when the length of a connecting wire resonates with the frequency (f_w) of the injected signal, according to the following expression:

$$f_w = \frac{c}{2l} \quad (1)$$

where

f_w —the frequency [GHz];

l —the wire length [m];

c —the electromagnetic wave propagation speed [m/s].

The most vulnerable cables are connected between the switch points on the electronic speed control board and the rotors at the ends of the arms.

3. EMC Regulations

The development of the unmanned aerial system (UAS) market in Europe has led to the need to harmonize regulatory requirements for the technical safety of these systems, including their resistance to electromagnetic interference. Today, electromagnetic compatibility (EMC) is one of the key aspects of UAV design and certification, both for operational safety and compliance with applicable European Union law. Drones, being electronic devices with a high degree of integration of communication, control, and navigation systems, are particularly susceptible to the impact of external electromagnetic fields, the intensity of which systematically increases in the operational environment. This applies to urbanized environments, where various emission sources are present—such as 5G cellular base stations, radar devices, high-voltage transmission lines, and industrial installations.

The Commission Delegated Regulation (EU) [3] establishes requirements for unmanned aircraft systems placed on the market in the European Union under the so-called open category. UAV manufacturers are obliged to carry out procedures to assess conformity with the requirements specified in the annex to the Regulation. This includes, among others, the obligation to consider the relevant harmonized standards, including those relating to electromagnetic compatibility. A UAV must meet the criteria for resistance to interference to be CE-marked and legally placed on the market. Importantly, in accordance with Article 20 of Commission Implementing Regulation (EU) [20], drones placed on the market before 1 July 2022 that do not meet the requirements of Regulation 2019/945 may continue to be operational in certain subcategories A1 and A3 under the so-called transitional rules, provided that operators meet the relevant operational requirements.

One of the basic legal acts regulating EMC issues in the EU remains Directive 2014/30/EU on electromagnetic compatibility [1]. According to its provisions, all electrical and electronic devices, including UAVs, must be designed in a way that allows them to function properly in a predictable electromagnetic environment, without causing excessive electromagnetic interference that could interfere with the operation of other devices. In practice, this means that drones should be resistant to at least an electromagnetic field strength of 10 V/m in the frequency range from 80 MHz to 6 GHz, which results from the requirements of the IEC 61000-4-3 standard [2], which is an element of many harmonized standards used in the conformity assessment of UAVs.

It should be noted that the level of 10 V/m may be insufficient in real operating conditions. Council Recommendation [21] on the limitation of public exposure to electromagnetic fields assumes permissible electric field strength levels of up to 61 V/m in the 2 to 300 GHz band, which indicates that UAVs may be exposed to significantly higher radiation levels

than the immunity threshold required for EMC certification. For military applications, the EMC immunity reference levels are even higher—for example, according to the American Standard Mil-Std-461G (RS103 procedure), the required level of immunity to radiated electromagnetic interference can reach up to 200 V/m [22]. This means that drones used in environments with high electromagnetic field intensity, such as the vicinity of military, industrial, or airport installations, must demonstrate significantly higher immunity than that required for operations in typical civilian conditions.

In the context of the above regulations, conducting the electromagnetic compatibility tests of UAVs should include both classical laboratory procedures and in situ field tests. The standard EMC testing process for UAVs should start with an analysis of electromagnetic hazards at the design stage and then include the measurements of radiated and conducted emissions and immunity in accordance with standards such as EN 61000-6-2, EN 55032, EN 301-489-1/-17, and IEC 61000-4-6 [23–26]. Tests in an anechoic chamber enable the precise assessment of electromagnetic emissions and radiation immunity at given field values up to 10 V/m or higher.

Experimental studies conducted in recent years confirm that exposure to a continuous electromagnetic field of 20–60 V/m causes significant interference in the operation of UAVs, especially in the field of navigation and communication. With continuous electromagnetic fields of 15–30 V/m, transmission delays, communication bus instability, and positioning anomalies occur, which create an operational risk for drones performing automatic flights.

Therefore, there is a need to revise the minimum immunity levels required for UAV certification, at least for platforms intended for operations in urban areas or near strong emission sources. It is proposed to implement a three-step UAV EMC assessment model:

- Baseline tests up to 10 V/m for recreational equipment and low-risk applications;
- Extended tests up to 30–61 V/m for commercial systems operating in urban environments;
- Immunity tests up to 200 V/m for military, rescue, or industrial platforms.

In summary, the electromagnetic compatibility testing of UAVs should be an integral part of the conformity assessment process, as a necessary condition not only for obtaining the CE marking but also, above all, for ensuring safe operation in an environment increasingly saturated with electromagnetic emissions. The EU regulations define the obligations of manufacturers and operators in terms of ensuring UAV immunity to interference. Therefore, EMC should be viewed not only as a certification formality but also as a critical element of the safety of unmanned systems, requiring the continuous updating of testing procedures and the adaptation of standards to technical and operational realities.

4. Investigation of UAV Vulnerability in Electromagnetic Environment

Published studies into the effects of electromagnetic interference on the electronic systems of UAVs have received increasing attention. Various methods have been proposed to explore the associated interference mechanisms associated with such interference, and these can be broadly categorized as experimental testing and computational simulation. Experimental testing allows for the practical validation of a drone's performance by simulating real-world operational scenarios under various electromagnetic conditions.

In this work, the adverse effects of the electromagnetic environment on UAVs were investigated in an anechoic chamber. This chamber is lined with ferrite and graphite absorbers on the walls and ceiling, providing a suitable test environment isolated from external electromagnetic radiation. This research was conducted to investigate the adverse effects of the electromagnetic environment on drones. The test setup was configured in compliance with the requirements of relevant EMC standards. Exposing a drone to these controlled conditions allows for the correlation of potential effects with the incident electric

field strength. The setup also enables an assessment of the influence of field polarization and the drone's orientation relative to the transmitting antenna.

The electromagnetic immunity test was conducted based on the MIL-STD-461G standard in accordance with the RS103 procedure, which requires the use of specialized equipment to generate and control an electric field of specified intensity and uniformity. The measuring station, setup for testing according to the diagram shown in Figure 2, includes the following equipment:

- An RF signal generator with a wide frequency range (10 kHz–18 GHz), capable of generating sinusoidal waveforms with a stabilized output level—SMB100A by Rohde and Schwarz.
- Power amplifiers matched to specific frequency bands (e.g., 30 MHz–1 GHz, 1–18 GHz), ensuring the generation of a field with an intensity of up to 200 V/m—BBA150 by Rohde and Schwarz and TWAL 0618-300, BLMA1829-4, and BLMA2640-5 by BONN Elektronik.
- A transmitting antenna set—BBAL9136, BBAE9179, STLP9128E, BBHA9120E, BHA0618, TC-SGH26, and TC-SGH40.
- Electric field probes (E-field probes) with known frequency characteristics, used to monitor field uniformity within the test volume—HI-6053 by ETS Lindgren.
- Control and data acquisition system, enabling automatic frequency sweeping, output power control, and the recording of the device under test responses—PC computer with the software.

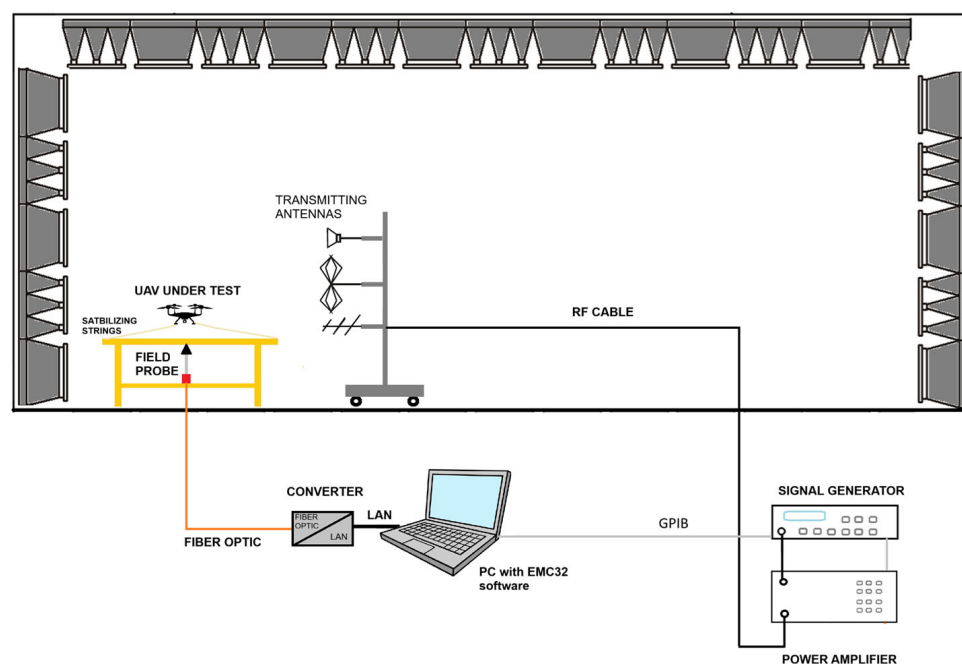


Figure 2. Block diagram of the test setup for examining drone immunity to the electromagnetic field in an anechoic chamber.

During laboratory tests, six popular models of commercial drones were analyzed, i.e., AE3 Pro Max, OVERMAX X-Bee Drone 9.5 Fold, LYZ RC Drone L600 PRO, DJI Mini 2, AE8 EVO, and DJI Phantom. The analyzed drones differ in terms of weight, image quality, flight time, and range; however, they all represent the current level of UAV technology used in the popular civilian sector.

The drone, as the Equipment Under Test (EUT), was placed on the test stand in a configuration corresponding to typical operating conditions. All subsystems, including communication, navigation, and sensors, were active. After the calibration of measurement

setup and probes, the process of electromagnetic field generation was initiated. During the experiment, the tested drone was secured to the table with tape, allowing only minimal lift. Testing was conducted with two antenna polarizations: vertical and horizontal. For the tested drones, measurements were performed in a horizontal flight plane, without changing the tilt or inclination relative to the antenna, simulating typical drone orientation during flight. During exposure, the drone's operational parameters were monitored, including data transmission, telemetry signals, control processor behavior, and power system stability. The view of the test system for UAV irradiation in the anechoic chamber is shown in Figure 3. During flight, the drone was exposed to increasingly stronger electromagnetic fields until it descended onto the table. The tape used ensured that no damage occurred to the walls of the anechoic chamber in the event of a loss of flight control.

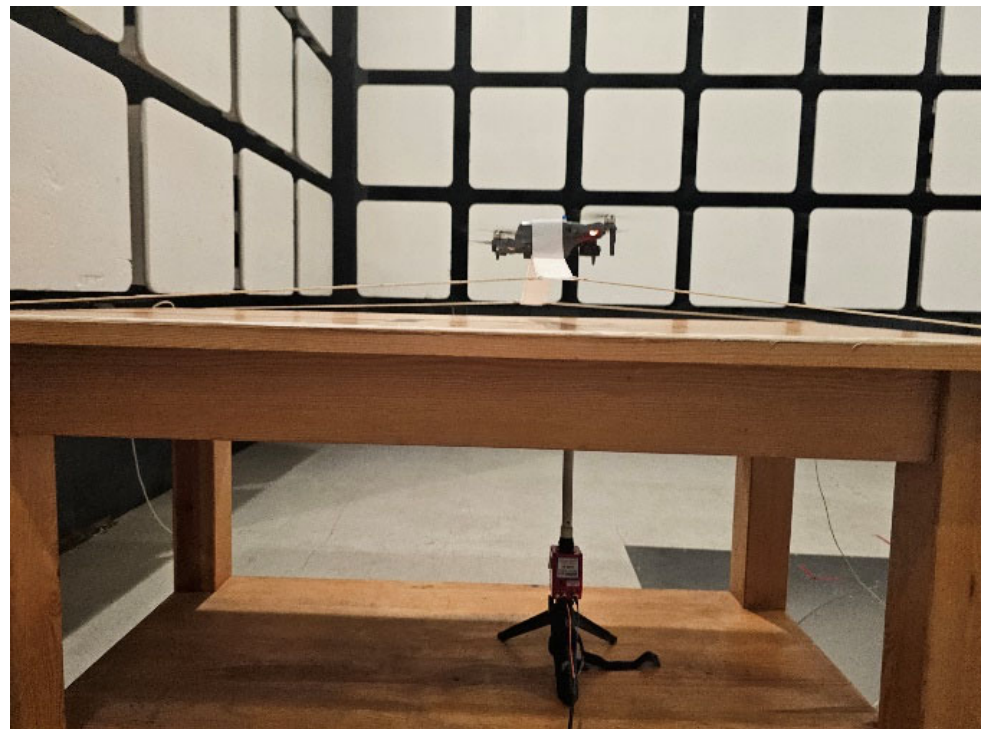


Figure 3. The drone fastens on the table in an anechoic chamber.

This study focused on frequencies emitted by cellular base stations' antennas. During the experiments, the electromagnetic field was generated in representative frequency bands used in cellular communications. The considered downlink frequency bands were as follows: GSM-900 (915–960 MHz), GSM-1800 (1805–1880 MHz), LTE-2100 (1900–2290 MHz), and LTE-2600 (2500–2690 MHz). For each of these frequencies, an electromagnetic field of a specified intensity of 10 V/m, 20 V/m, and 30 V/m was generated, and the drones were exposed for a defined period during flight while monitoring their parameters. With these frequencies drones were exposed to vertical as well as to horizontal field polarizations. Base station antennas are "cross-polar" ($\pm 45^\circ$); therefore, the emitted radiation has both vertical and horizontal polarizations. It has been observed that vertical polarization with an electric field strength up to 30 V/m does not cause negative impacts to drones' flights. On the other hand, horizontal polarization, with the field value of up to 20 V/m, caused unstable flights; however, they did not fall on the table, and they continued the operation when the electromagnetic field was switched off. The scale of instability of the flights depended on the drone type and not on the drone model. Electric field strength with the level of 30 V/m caused changes in rotational drone speed propellers, leading to chaotic flight directions or to falls. For some drone types, one or some propellers were turned off. However, after the

test, all functions can be restored. In a real scenario, a drone that chaotically falls on the ground can be mechanically damaged.

It was observed that horizontal polarization has a significantly greater adverse impact on drones than vertical polarization. This is because the drone's cables are primarily oriented horizontally, which results in better energy coupling from the incident field. With horizontal polarization, it was found that, at an electric field strength of 30 V/m or higher, commercially available drones began to experience erratic flight or an uncontrolled descent. This value can therefore be considered the effective immunity threshold for safe flight under these conditions. Stable flight requires that the current supplied to each motor is precisely determined by the onboard microcomputer. However, the additional, induced parasitic current perturbs these control signals, disrupting the synchronous operation of the propellers and compromising flight stability.

5. Base Station Downlink Radiation

Cellular base station (BS) antennas are primary sources of the electromagnetic field emitted into the environment. Since power density decreases with the square of the distance from the source, the power radiated from these antennas must be sufficiently high to ensure effective communication with user terminals, which may be located far away from the base station. From this reason, power density can have high intensity close to antennas. To protect the public from the potential adverse effects of this radiation, permissible exposure levels have been established by law. These limits on electric field strength are designed to protect individuals against known thermal effects and against currents induced within the body. These public safety standards are widely recognized and adopted by European and international organizations [21,27].

Established guidelines stipulate that EM fields from mobile base stations can reach levels of up to 28 V/m at frequencies below 400 MHz and up to 61 V/m at frequencies above 2000 MHz. In the frequency range from 400 MHz to 2000 MHz, the permissible exposure level varies as a function of frequency, with the value between 28 and 61 V/m [27]. These reference levels, which define the permissible exposure threshold for the public, are illustrated in Figure 4.

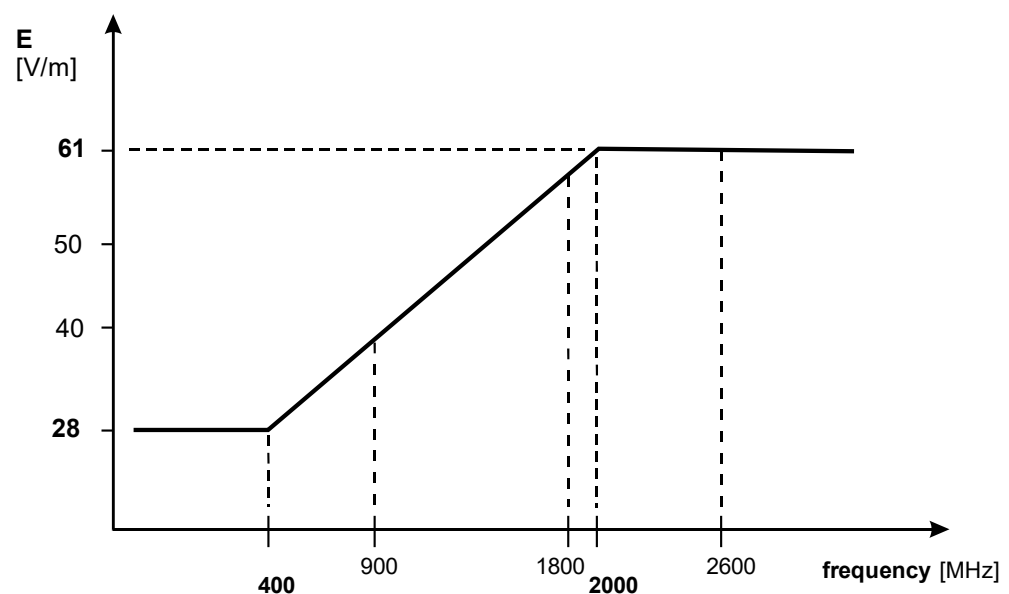


Figure 4. Reference levels of electric field strength for public exposure.

While the permissible exposure levels (illustrated in Figure 4) are maintained in areas accessible to the public, the radiation in the immediate vicinity of a base station antenna

can be significantly higher. Consequently, the field strength in this area can far exceed the immunity threshold mandated by EMC regulations for consumer electronic devices. As a result, manufacturers cannot guarantee the proper operation of their products under such intense radiation.

Given these conditions, it is necessary to determine the practical safe operating distance from base station antennas, defined here as the point where the value of electric field strength is higher than 30 V/m. The distance was determined based on the relationship of electric field strength (2). This formula refers to the main lobe and free space conditions.

$$E = \frac{k\sqrt{P}}{R} \quad (2)$$

where

k —the constant, $k = 7$;

R —the distance from the antenna [m];

P —the power (ERP) [W];

E —the electric field strength [V/m].

Therefore, the distance R can be expressed as follows:

$$R = \frac{k\sqrt{P}}{E} \quad (3)$$

For this calculation, a maximum effective radiated power (ERP) of 40 dBW per sector was assumed, in accordance with the EU regulations [20]. The distance for such power has been calculated using the relationship (3). Considering $P[\text{ERP}] = 40$ dBW and an electric field threshold of $E = 30$ V/m, the safe operating distance (R) was calculated to be 20 m from the antenna. This calculated distance is valid within the antenna's main radiation lobe. In the direction of the side lobes, the electric field strength is lower, as defined by the antenna's radiation pattern. However, along the main radiation axis, the field strength can exceed the drone's immunity threshold at any point within $R = 20$, and the risk adverse effects must be taken into account. It should be noted that the value of $\text{ERP} = 40$ dBW, taken for calculation, represents the maximal power feeding sectorial antennas. For lower power base station antennas, the separation distance (R) can be proportionately smaller.

6. Conclusions

This paper has presented an investigation into the safe flight of unmanned aerial vehicles (UAVs) in an electromagnetic environment. The proper operation of a drone's electronic systems is contingent upon meeting electromagnetic compatibility (EMC) requirements. While the existing EMC standard sets the immunity threshold for commercial drones at 10 V/m, public safety guidelines permit the environmental field from sources like base station antennas to reach up to 61 V/m. To assess the vulnerability of drones exposed to such high intensity levels, experiments were conducted out in an anechoic chamber. It was found that, when the electric field strength is 30 V/m or higher, commercially available drones experience flight instability leading to an uncontrolled descent. Considering the maximum effective radiated power of base station antenna is 40 dBW per sector, with an electric field level of $E = 30$ V/m, a minimum safe operating distance of $R = 20$ m from the antenna was determined. Adherence to this safe distance is strongly recommended for all drone operators to prevent EMI-induced flight failure.

In the future, similar experiments will be investigated in the electromagnetic environments in the vicinity of airports, where the level of pulsed microwaves can be even stronger compared to cellular base station radiation, and where the consequences of uncontrolled drone flight could lead to catastrophic consequences.

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