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Airport electrification and electromagnetic emissions – standards and challenges

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Abstract

The growing demand for electrification increases the likelihood of airport system interference caused by electromagnetic emissions. Studies have shown that equipment, installations, and vehicles (including trains, cars, and aircraft) may exceed emissions limits established by many airports. While minor airport system disruptions, such as radio noise squelch, have been present for years, rising emissions may pose risks to critical radio communication and navigation systems potentially leading to severe consequences.

This work provides an overview of airport-related electromagnetic emission standards, comparing product-specific standards with current airport emission regulations. The analysis evaluates emission limits across various standards, emphasizing measurement methods, such as distance, bandwidth, and detectors, alongside their underlying principles. The paper outlines key challenges which may impact airport operations as electrification expands within both the airport environment and aircraft themselves.

Results highlight the complexity of diverse airport environments, showing that a single standard across an entire airport is impractical. Some equipment will inevitably produce emissions, making product (family) standards, which are hierarchically superior to generic ones, a priority. Notably, road vehicles, high-power equipment and electronic discharge machining products may emit significantly more than current regulations permit. Furthermore do preliminary measurements indicate that electrically propelled aircraft, airport installations and ground power units generate substantial emissions, with high likelihood exceeding defined limits.

Overall, the findings presented indicate that further investigations are relevant for standardisation, its implementation, and the impact of emissions from various sources on airport operations.

Keywords: Electromagnetic compatibility (EMC), Electromagnetic emissions, Sustainable aviation, Airport environment, Standards and regulations

1 Introduction

The increasing demand for electrification, partly driven by sustainability goals, has led to a surge in electrical systems increasing the likelihood of extensive electromagnetic emissions. Studies [1, 2] indicate that both sustainable technologies, such as photovoltaic installations, vehicle chargers, and electric transportation (including trains, cars, and aircraft), and conventional electronic products like information signs, switching regulators, and industrial systems, can contribute to elevated electromagnetic emissions. These emissions stem from increased power levels and high-frequency switching, potentially leading to significant electromagnetic interference with other systems. This is particular concerning for sensitive aviation electronics, where disruptions can have serious consequences.

Minor disturbances in aviation systems, such as radio noise squelch have been documented for years [3, 4]. However, the increase of emissions may pose greater risks, potentially causing more frequent and severe disruptions to both human- and machine-controlled critical radio communication and navigation systems, leading to severe operational consequences.

Electromagnetic emissions are regulated by various legislations, standards, and guidelines. However, due to the complex regulatory framework at airports, general regulations may not always be sufficient to ensure safe air travel, making additional requirements necessary.

At the same time, manufacturers and operators often struggle to navigate and comply with the extensive rules outlined in both common regulations and airport-specific requirements. In Sweden, airports have established a standard that products must meet to be permitted within airport vicinities. While defining a single standard helps streamline compliance for both airports and product providers, it remains uncertain whether this simplified approach is sufficient or realistically viable.

The aim of this paper is to facilitate the ongoing electrification of airports and aircraft with regard to electromagnetic emissions, regulations, and their impact in the airport environment. With this goal, the work provides an overview of airport-related electromagnetic emission standards, comparing product-specific standards with current airport emission requirements. The paper further outlines and exemplifies a number of challenges that may affect airport operations given the increase in electrification of the airport environment as well as the aircraft themselves. The following section introduces the basics of *Electromagnetic Compatibility* (EMC) as well as the relevant legislation, while section 3 presents an overview of different standards and the organisations responsible for them. Thereafter, section 4 examines differences between standards and provides a brief explanation of the measurement methods, and section 5 outlines airport regulations and current requirements. Continuing, section 6 discusses identified challenges that may affect future airport operations and section 7 offers a discussion on key findings and implications. Finally, the paper is concluded in section 8.

2 Introducing Electromagnetic Compatibility

Electromagnetic emissions are a part of EMC. As in many other fields, they are governed by legislation.

2.1 What is Electromagnetic Compatibility

Despite its critical role in electronics, EMC is often overlooked due to its invisible nature and a general lack of awareness. EMC ensures electrical and electronic equipment functions as intended without causing or experiencing interference from other devices. While all equipment emits electrical energy, unintended interactions can occur. Unlike radio transmitters and receivers, which are designed to emit and receive energy, other devices may inadvertently also do so. Systems can emit or receive unwanted energy, potentially disrupting their own function or that of other devices. Electromagnetic energy is defined in the form of conducted emissions: electrical voltages or currents travelling through cables, or radiated emissions: electromagnetic fields dispersing into a non-conductive medium (usually air).

For uninterrupted operation, a system must be able to withstand a certain level of electromagnetic interference. This resilience is assessed based on the applicable standards and is referred to as either electromagnetic immunity (the ability to withstand) or electromagnetic susceptibility (the likelihood of malfunctioning). EMC regulations ensure that a product does not emit excessive electromagnetic energy and remains resistant to predefined levels of interference.

The consequences of EMC issues at airports depend on the affected systems. Some disruptions may result in minor inconveniences, such as malfunctioning information signs. However, more severe, and potentially fatal, problems can arise if electromagnetic interference compromises *Communication, Navigation and Surveillance* (CNS) systems, directly impacting the ability to control aircraft and other critical airport operations.

This study focuses on radiated emissions in the 30 to 1000 MHz frequency range, as many aviation systems [5] and ground radios operate within this band. It is well-defined in standards and remains low enough to capture distortions from low-frequency switching converters.

2.2 EMC Legislation

Legislation mandates that products must be safe to operate. The key regulations concerning EMC are the European regulation (EU) 2018/1139 [6], the *Electromagnetic Compatibility Directive* (EMCD) [7] and the *Radio Equipment Directive* (RED) [8], which govern non-intentional and intentional emitters. The directives stipulate that technical documentation, supported by the EMCD [9] and RED [10] guides, along with tests conducted in accordance with relevant standards, should demonstrate a presumption of conformity.

3 About Standards

Due to the vast variety of products, numerous standards exist. Most standards apply to common consumer products, but there are also specialised aviation and military standards. Depending on the product and its intended application, one or more standards from these categories should be selected to ensure compliance. In this work the term "common standards" refers to standards applicable to general products, excluding aviation-specific and military regulations.

3.1 Common Standards

The *World Trade Organization* (WTO) has defined the *Technical Barriers to Trade* (TBT) agreement to ensure fair international trading. With regards to standards they have founded the *World Standards Cooperation* (WSC) with the members *International Organization for Standardization* (ISO), *International Electrotechnical Commission* (IEC) and *International Telecommunication Union* (ITU) to create global common standards. The *International Special Committee on Radio Interference* (CISPR) hosted by the IEC is a cooperation of seven international organisations which focus on controlling electromagnetic interference. Other organisations may also create such standards, but they may not carry the same legal recognition as standards established by WSC members [11].

European common standards, are managed by the three *European Standards Organization*s (ESOs): *European Com-*

mittee for Standardization (CEN), *European Committee for Electrotechnical Standardization* (CENELEC), and *European Telecommunication Standards Institute* (ETSI). The standards developed may be direct adaptations of global standards or independently developed (so-called "home-grown" standards). CEN and CENELEC guide technical experts from national member organisations to manage standards, whereas ETSI develops its standards through contributions from its own technical members. [11].

European Norm (EN) standards are developed in compliance with European legislation and approved by *European Union* (EU) and *European Economic Area* (EEA) members. EN standards are harmonised through publication in the *Official Journal of the European Union* (OJEU). According to the EMC guide [9], harmonised standards should be prioritised whenever possible. EN standards are adopted at the national level through each country's respective standardisation organisations [11]. In Sweden these adaptations are noted by *Swedish Standard* (SS) such as:

IEC 61000	$\leftrightarrow$	EN IEC 61000	$\leftrightarrow$	SS-EN IEC 61000
CISPR 16	$\leftrightarrow$	EN 55016	$\leftrightarrow$	SS-EN 55016

In this work the most up to date edition of the standards have been used, unless otherwise specified by written regulations.

The common standards are organised into a hierarchical structure with four distinct classes [9, 12]:

1. EMC Product Standards: Developed for specific products or environments, these standards may exist independently or serve as amendments to broader regulations. They generally reference product family standards and basic publications but can also introduce stricter or more forgiving requirements.

2. EMC Product Family Standards: Covering groups of products with similar functions in comparable environments, these standards should be used when no appropriate product-specific standards are available.

3. Generic EMC Standards: Applicable to products that do not fall under product-specific or product-family standards. While these standards provide a solid technical foundation for certification, they specify only a limited number of tests. In terms of emissions, three generic EMC standards exist for residential, commercial and light-industrial, and industrial locations.

4. Basic EMC Publications: Define fundamental methods for performing EMC measurements. These publications comprise a mix of standards and technical reports, which serve as references for other EMC regulations. The core basic EMC publication is the CISPR 16.

3.2 Aviation Standards

Aviation equipment must be significantly more robust than generic equipment, as any fault can have fatal consequences. Therefore, aviation equipment must be certified according to specialised aviation standards. Many aviation related standards and regulations come from the *International Civil Aviation Organisation* (ICAO), *European Union Aviation Safety Agency* (EASA) and the *European Organisation for Civil Aviation Equipment* (EUROCAE).

ICAO, established following the Chicago Convention in 1944, develops Annexes and *Procedures for Air Navigation Service*s (PANSs) to define *Standards and Recommended Practice*s (SARPs). In relation to EMC, the most relevant ICAO documents are the Annex 10 series [5] and Document 9718 [13], which outline technical aeronautical telecommunications requirements and guidelines applicable to aviation CNS systems. EASA is the European representative in ICAO.

EUROCAE is an aviation business association, where aviation businesses cooperatively define standards. Although classified as a European organisation, it has global affiliations, largely due to its collaboration with the *Radio Technical Commission for Aeronautics* (RTCA) in the United States and *Society of Automotive Engineers* (SAE) international. The primary environmental standard developed by EUROCAE which includes EMC is the ED-14 [14], which is identical to the RTCA DO-160 and ISO 7137, and is supplemented by ED-234 (DO-357). Additionally, EUROCAE and SAE have published the "Guide to Civil Aircraft Electromagnetic Compatibility (EMC)", documented as ED-248 [15] while SAE defines it as an *Aerospace Recommended Practice* (ARP) designated SAE ARP 60943.

3.3 Military Standards

Military equipment is governed by distinct regulations, often imposing stricter requirements, which has led to the development of specialised military standards. These standards are not exclusive to military applications, commercial manufacturers can also adopt them to certify their products. Although demonstrating presumption of conformity to generic legislation is more challenging with these standards, they are frequently applied in commercial sectors due to their rigorous criteria, providing a stronger indication of product quality and reliability. Key military EMC standards include MIL-STD-461 [16], MIL-STD-464 [17] and DEF STAN 59-411 [18] .

4 Analysis of Standards

Standards help to ensure that products operate safely in accordance with defined legislation. However, both the fundamental principles and the finer details of these standards can vary depending on the application.

There are various methods for conducting emission measurements, each influenced by specific parameters that can significantly impact the results. Factors such as distance, filter bandwidth, detectors, and antenna types are carefully selected according to established standards, each serving a specific purpose. Due to these variations, direct comparisons between standards are not feasible without a thorough understanding of the reasoning behind parameter selection. A solid grasp of the fundamental principles is essential to comprehend why a particular measurement method is chosen.

4.1 Purpose of Standards

Different standards define product safety in various ways. Most common standards focus on emission levels, requiring products to remain within set limits to pass certification. Additionally, they must be immune to expected environmental emissions in their intended operating conditions.

Aviation-specific equipment standards, such as EUROCAE ED-14G, ensure that aircraft systems function reliably without interference. These standards impose high immunity requirements to protect against both internal and external emissions. Since aircraft primarily operate in airspace where distances to other systems are relatively large, certification processes typically do not focus on external emissions or emissions from the aircraft in its entirety.

Military standards function similarly to aviation standards, prioritising the safety of the aircraft. Some, such as MIL-STD-464D, briefly address aircraft emissions in its entirety, but primarily within "*Emission Control* (EMCON)" situations where only mission-essential emissions are permitted [19]. In such cases, complete radio silence may be required. These levels of emission are almost impossible to achieve in current day urban areas.

Additionally, aviation CNS standards, such as ICAO's Annex 10, focus on achieving a specific *Signal-to-Noise Ratio* (SNR) rather than absolute emission levels. While this approach is effective, it relies on a regulated maximum signal strength. Consequently, increased noise levels lead to a reduced SNR, which may negatively affect system performance. A decrease in performance does not necessarily mean system failure. However, it may result in a reduced effective range or potential blind spots, where the required SNR is not maintained over longer distances or in specific areas.

4.2 Measurement Methods

There are various methods and parameters for EMC measurements, with standards defining these based on the product type, application, and expected outcomes. While a comprehensive review of all differences and justifications is impractical, key distinctions will be highlighted.

4.2.1 Distance

Since electromagnetic fields spread out and weaken over distance, defining an accurate measurement distance is crucial. The appropriate distance is often specified in standards and varies depending on the application. For example, products used inside a building operate in closer proximity to users and other equipment compared to systems in a factory or outdoor environments. Common standards typically specify measurement distances of 3 or 10 meters, though 1 and 30 meters are also used for automotive and larger systems.

Aviation and military standards frequently adopt a 1-meter measurement distance, as the primary concern is the field's effect within a vehicle or near humans. While longer-distance measurements are performed, strict requirements make obtaining accurate results challenging. Increased distances result in weaker signals, which can be difficult to distinguish from background noise. For very large objects, such as aircraft or major installations, measurements might anyway need to be conducted at sufficient distance to ensure reliable results based on received emission from the entire system.

4.2.2 Bandwidth

To measure a specific frequency using a measurement receiver, a filter should be applied to remove all signals not of interest. Standards define the characteristics of this *Resolution Bandwidth* (RBW) filter. According to these standards, compliant EMC measurements must be conducted using a 6 dB RBW, as found in EMI-receivers. In contrast, generic 3 dB Gaussian filters in spectrum analysers lack the necessary selectivity and can only be used for estimation measurements.

Table 1: Resolution bandwidth for different standards

Frequency [MHz]	CISPR16-1-1: 2019 [20]	ED-14G [14]	MIL-STD-461G [16]
30 - 100	120 kHz	-	100 kHz
100 - 400		10 kHz	
400 - 960		100 kHz	
960 - 1000		1 MHz	

As outlined in Table 1, different standards utilise varying RBW filters. The basic EMC publication CISPR 16-1-1 [20] specifies a RBW for the 30 - 1000 MHz range (C and D bands) of 120 kHz, while the military standard adopts a similar 100 kHz filter. However, some standards, such as vehicle standard CISPR 12 [21], allow broadband measurements with RBW filters up to 1 MHz. These filters are useful for measuring broadband emissions but are unsuitable for aviation system measurements, where many systems operate closely together with narrow channels.

Aviation standard ED-14G applies different RBWs across the frequency range to improve measurement accuracy in the lower bands but it does not measure radiated emissions up to 100 MHz. Instead, these frequencies are addressed through conducted / cable emission tests, which extend up to 152 MHz.

Certain standards permit RBW adjustments, requiring corresponding modifications to limit values, unless otherwise specified. Additionally, the standard 6 dB filters defined in the standards often lack sufficient selectivity to meet strict aviation requirements defined by ICAO, such as adjacent channel rejection, as outlined in Annex 10.

4.2.3 Detectors

Electromagnetic fields typically fluctuate in both frequency and time domains, necessitating various detectors to accurately characterise different types of disturbances.

- The peak detector captures the highest amplitude of a signal instantly, making it the fastest and most sensitive detector. It is commonly used in aviation and military standards for worst-case analysis but occasionally also in common standards for EMC testing.

- The quasi-peak detector - Applies time-weighted averaging, considering both signal amplitude and *Pulse Repetition Frequency* (PRF). It is historically used to assess interference affecting voice and broadcast communications, something that may no longer be entirely accurate given advancements in modern digital telecommunication systems [22].
- The average detector takes PRF into account but does not incorporate time-weighting parameters. While some standards utilise average detection in the 30 - 1000 MHz range, it is more commonly applied to conducted emissions below 30 MHz and radiated emissions above 1 GHz.
- The RMS-average detector is relatively new and designed for modern digital communication systems, particularly those operating above 1 GHz. It has the potential to overcome some of the drawbacks of the quasi-peak detector. However, as of this writing, its application remains limited [23].

Comparing different detectors may result in skewed measurements, as they are influenced by PRF. Quasi-peak detection, commonly used in generic standards, provides better visualisation of signal characteristics over time. However, in aviation, even short disruptions can have significant consequences.

According to CISPR 16-1-1, results for peak and quasi-peak detectors can be equal for high PRF, whereas for low PRF, peak levels can be up to 43.5 dB higher than quasi-peak levels. Since the PRF of interference is often unknown, comparing different detectors can be challenging.

5 Airport regulations and requirements

Regulation (EU) 139/2014 mandates that EU member states have to provide a safe operational airport environment, including maintaining a high-quality radio spectrum to prevent aviation system interference. In Sweden, this regulation is incorporated into Aviation Regulation 2010:770 and Swedish Transport Agency's Statute 2019:19. Its implementation is further outlined in ICAO's Annex 10 and guide Doc 9718.

At the global level, ICAO oversees regulation, while EASA is responsible at an European level, and the Swedish Transport Agency manages Swedish regulations. However, airports themselves determine how to fulfil these requirements. Consequently, airports may enforce regulations beyond those set by (EU) 2018/1139, the EMCD, RED, or common standards.

In Sweden two operators guide airport EMC requirements, the Swedish Civil Aviation Administration (Luftfartsverket) and state-owned airport owner and operator Swedavia AB. Luftfartsverket has specified the EN 61000-6-3:2007 [24] standard [25], which applies to emissions in residential, commercial and light industrial environments. Swedavia has in their Airport Regulations [26] specified the EN 61000-6-3 additionally enforcing stricter requirements for emissions in the 108 - 137 MHz and 380 - 430 MHz bands in certain outdoor areas to enhance radio communication.

6 Identified Challenges

Based on observations regarding the standards, several challenges have been identified. These challenges stem from findings in existing standards and regulations, as well as industry trends. To quantify some of these challenges, preliminary measurements have been conducted to perform a comparison with real data.

The goal of highlighting these challenges is to raise awareness about the effects of electromagnetic emissions to support the ongoing electrification of airports and aircraft. Defining the necessary requirements is complex, but identifying these challenges can help guide the development of future regulations and maintaining a safe electromagnetic environment on and around airports.

6.1 Various Environments within an Airport

An airport is a dynamic environment where various disciplines intersect, making it challenging to establish uniform requirements for the vast array of equipment within the airport area. Some standards highlight the need for additional or specialised requirements, as generic standards may not fully address the unique complexities of airport operations.

Luftfartsverket has established a single zone extending 3 km from each edge of the runways. Swedavia, on the other hand, has defined up to three zones: one at 6 km, another at 4 km, and one within the terminal area. Additionally, within the terminal area, they consider whether a location is indoors or outdoors.

Having EMC zones is beneficial, however the current designated zones defined by the airports may be too extensive compared to the described zones in the standards. Possible examples of EMC zones include offices, control rooms, technical rooms, public walkways, and gate areas. These smaller zones allow for better control of emission requirements and standardisation compared to a single zone encompassing the entire terminal. Each product adheres to its own standard and environment, and defining a single zone for a wide range of products may not be feasible for implementation.

6.2 Enforcing self-defined Requirements

Some manufacturers or operators impose additional requirements beyond existing standards. Typically, self-defined requirements should be stricter than official regulations. However, this means that products certified under standard regulations may not necessarily perform adequately in environments where these additional requirements apply.

As these requirements are often not traceable to official regulations, entities who define additional requirements should determine how they verify compliance.

Luftfartsverket and Swedavia have introduced additional requirements to enhance and safeguard the operation of aviation CNS- and other radio-systems. While these requirements might be beneficial, almost no commercial product has undergone testing based on them. Therefore, additional evaluations are required for on-site use.

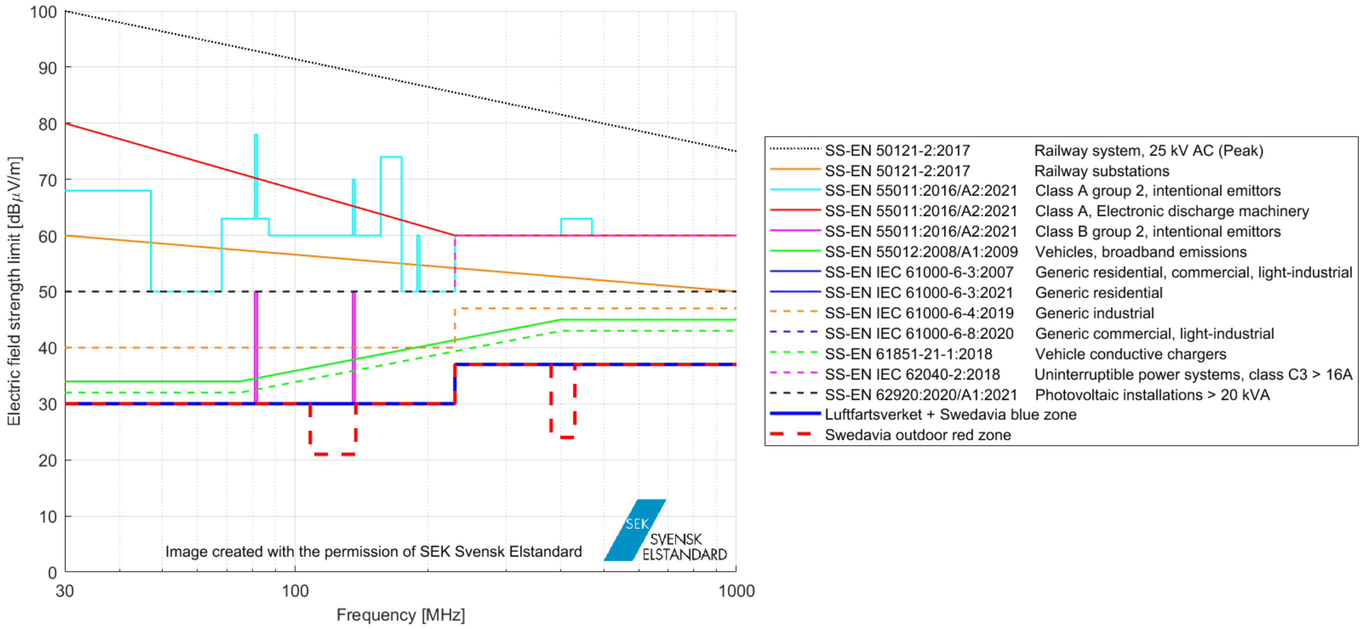

Figure 1: Emission limits specified by analysed common standards, compared to current airport regulations. Limits are based on the quasi-peak detector at a distance of 10 m using a 120 kHz RBW, apart from one railway standard utilising peak detector.

Testing can be performed on all products purchased and used by the airport and its personnel. However, enforcing these requirements on passengers and other non-airport-related individuals presents challenges. Continuous monitoring of the radio spectrum is one possibility for the operator to ensure compliance.

6.3 Overlapping Standards

The EMCD mandates that standards be applied in a hierarchical order. Since no single standard encompasses an entire airport, it may be reasonable to adopt a generic standard. However, most equipment found on airports adheres to the EMCD hierarchy and is certified according to product-specific or product-family standards.

Although most of these standards share fundamental principles derived from basic EMC publications, similar to generic EMC standards, deviations may still occur. As a result, a product might be correctly certified yet emit more electromagnetic emissions than generic standards permit. Examples of such deviations are:

- Road vehicles: The main product family standard for vehicles (CISPR 12), which also forms the basis for many vehicle-specific standards, allows increased emission levels. This is partly due to vehicle systems generating signals that fluctuate in frequency and energy with varying engine speed, such as ignition systems and electric drive units.

- High-power equipment: Airports house numerous high-power installations and products. Non intentional emitters for industrial applications, classified by CISPR as "class A", may emit significantly more emissions than household, commercial or light industrial products (class B). Standards even define higher emission limits for equipment exceeding 20 kVA such as *Ground Power Unit*s (GPUs) [27], photovoltaic installations [28] and uninterruptible power systems [29].

- Electronic discharge machining: Systems described in CISPR 11 [30], such as welding equipment release substantial energy in controlled discharges, resulting in high electromagnetic emissions. Minimising these emissions is challenging because doing so could compromise the intended functionality of the equipment, something specifically accounted for in its corresponding standard.

Figure 1 visually represents limits defined by varying common standards. The standards that have been analysed are also summed up in Table 2, where both the Swedish standard and the equivalent global standards are listed.

In the figure, the examples are represented as follows: the green line corresponds to road vehicles, the orange dashed line signifies non intentional emitters for class A high-power equipment below 20 kVA, the black dashed line visualises photovoltaic installations above 20 kVA, and the red line denotes electronic discharge machining. The (dotted) dark blue lines represent the identical limit defined by generic residential, commercial and light industrial standards, Luftfartsverket and Swedavia's blue zone. The red dashed line visualises the requirements defined by Swedavia outdoor in the red zone. Included are also other analysed standards. The black dotted line is a peak limit of the European train standard EN 50121-2 and is not defined by the IEC or CISPR.

It can be noted that the majority of the examined standards have emission limits that exceed the emission limits set by both the generic standard defined by Luftfartsverket and the

Table 2: Analysed common standards

Analysed standard	Equivalent standard	Ref
SS-EN 50121-2:2017	EN 50121-2: 2017	[31]
SS-EN 55011:2016/A2:2021	CISPR 11:2015/A2:2019	[30]
SS-EN 55012:2008/A1:2009	CISPR 12:2007/A1:2009	[21]
SS-EN IEC 61000-6-3:2007	IEC 61000-6-3:2006	[24]
SS-EN IEC 61000-6-3:2021	IEC 61000-6-3:2020	[32]
SS-EN IEC 61000-6-4:2019	IEC 61000-6-4:2018	[33]
SS-EN IEC 61000-6-8:2020	IEC 61000-6-8:2020	[34]
SS-EN 61851-21-1:2018	IEC 61851-21-1:2017	[35]
SS-EN IEC 62040-2:2018	IEC 62040-2:2016	[29]
SS-EN 62920:2017/A1:2021	IEC 62920:2017/A1:2021	[28]
Luftfartsverket + Swedavia	IEC 61000-6-3:2006 [24]	[25]
Swedavia outdoor red zone	-	[26]

limits established by Swedavia. In theory, this implies that products tested under different standards should either undergo reanalysis or be restricted from the premises. However, in practice, many products, especially those brought in by travellers, cannot be outright prohibited from airport premises, despite potential deviations in their emission performance.

6.4 Aircraft as Emission Source

According to European regulation (EU) 2018/1139 [6], airborne equipment is dismissed from the EMCD and the RED regulations, assuming that aviation certification ensures compliance. However, aviation standards do not account for emissions from an aircraft as a whole, which may interfere with airport operations.

This issue was highlighted by CENELEC in a 2000 report [36], where researchers found that comparing standards was complex but concluded that overall aircraft emissions should remain within defined limits as long as certification requirements were met by an aircraft. However, the standard used in that report is now obsolete, and newer regulations impose stricter requirements. Additionally, aircraft complexity has increased and electric aviation has a far more significant role today than it did in 2000.

Since most aviation standards apply to subsystems rather than entire aircraft, they cannot be directly compared to standards and requirements for entire systems. However, they do provide an indication of expected emission levels. The standards analysed are summed up in Table 3.

Table 3: Analysed aviation / military standards

Analysed std.	Application	Ref
ED-14G	Airborne equipment	[14]
ED-14G, adj.	ED-14G adjusted to CISPR method	-
MIL-STD-461G	Military subsystems and equipment	[16]
MIL-STD-464D	Military systems	[17]
Luftfartsverket	EN 61000-6-3:2007 [24]	[25]
Swedavia red	Swedavia outdoor red zone	[26]

While military standards have a bandwidth similar to airport requirements, the aviation standard ED-14G incorporates multiple bandwidth changes, as defined in Table 1. It specifically states that bandwidth correction should not be applied, an approach that makes sense from a testing perspective. However, when comparing the standard to airport regulations, applying these corrections provides insight into results based on the CISPR filter defined by airports.

Additionally, the military EMCON limits specified in MIL-STD-464D are defined at a distance of either 1 km or 1 nautical mile with a 30 kHz bandwidth. This limit has been adjusted to 10 m with 120 kHz RBW for the analysis. From the comparison was found that the majority of the aviation standards allow peak emission values that are higher than the current limits valid for quasi-peak set forth at Swedish airports. As stated, a direct comparison is dependent on in-depth knowledge of the signal properties.

As of today, aviation EMC standards are written for the industry as a whole, with no specific regulations for electric, hydrogen, or hybrid aircraft. This lack of tailored standards results in gaps in certification concerning EMC. EASA excludes tests that are not applicable for such aircraft, however it is not clear if the added electric propulsion parts are tested sufficiently with regards to electromagnetic emissions towards an external target, such as CNS systems at an airport.

Preliminary measurements indicate that electric aircraft emit significantly more electromagnetic emissions than combustion propelled aircraft. Figure 2 visually represents measured emissions from an EASA certified aircraft propelled by a single electric engine compared to a similar-sized aircraft propelled by a single internal combustion engine. To perform the measurement, a Chase CBL 6112 antenna has been used in combination with a Rohde & Schwarz ESPI test receiver utilising a peak detector. Airports specify quasi-peak limits, therefore a direct comparison would also here require additional knowledge on signal properties.

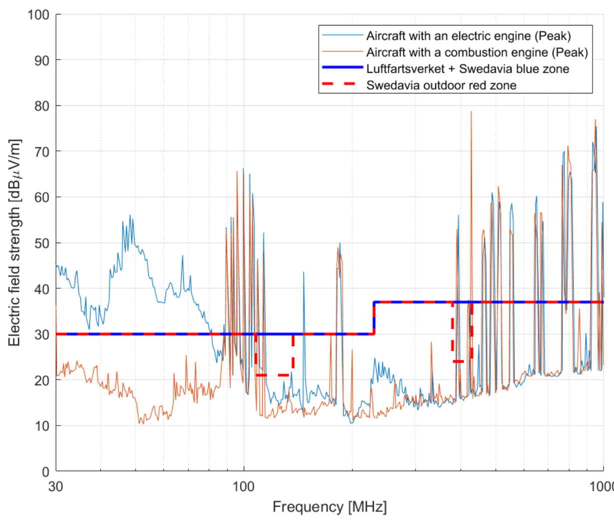

Figure 2: Measured electric field strength from an electric aircraft compared to a similar internal combustion propelled aircraft. Measurements were performed at a distance of 10 m using a 120 kHz RBW and peak detector. Results have been analysed against the quasi-peak limits defined by the airport.

Experience shows that the quasi-peak values received from switching drive systems systems often yield only a few dB lower readings than the peak values. It should be noted that the measurements were performed outdoors, meaning that other permitted emissions, such as radio, television, and mobile phone transmissions, were also detected. Nevertheless, the data shows that emissions from the electric aircraft, displayed in blue, are higher in multiple frequency ranges when compared to those from the aircraft with an internal combustion engine, seen in orange. Most dominant is the increase below 80 MHz.

The emissions are highly likely to exceed the limits set by Swedish airports and may also surpass the now-obsolete thresholds outlined in CENELEC's report.

6.5 Certification of Installations

Products that comply with the EMCD, RED, and other directives if applicable, shall bear the *European Conformity* (CE) marking. A common misconception is that using CE-marked (sub)systems automatically results in a compliant installation, this is however rarely the case. CE marking can also imply conformity with other directives or standards not applicable to the intended use.

The overall EMC performance of an installation further depends on the number of subsystems, number and routing of interconnections, environment and much more [37]. Contractors installing and maintaining installations shall refer to handbooks, guidelines, and installation documents from various institutes to obtain guidance regarding EMC.

Certification of installations is already a complex process in standard cases. The additional requirements set by the airport organisations introduce further regulations that must be considered. This means that generic guidebooks alone may not be sufficient for airport environments. Ultimately, the only reliable method to ensure compliance with all regulations is through measurements.

Installations are fixed systems that come in various shapes and sizes. A relatively simple example is a light fixture. While fixtures, lamps, drivers and their cables are typically tested as individual products, with their own CE markings, once installed in a specific location, they are classified as installations. The number of fixtures and the positioning of cables play a crucial role in EMC.

Figure 3 illustrates the emissions up to 300 MHz measured inside an airport arrival hall, showing a significant difference depending on whether the lights are enabled, shown in blue, or disabled, shown in orange. Measurements have been performed using an Aaronia 20100E antenna connected to a Keysight N9934B signal analyser. Apart from the received tower signal with 9 kHz RBW do all results utilise 120 kHz RBW.

At the tower frequency, measurements revealed a 30 dB variation depending on the state of the lights. Additionally, it was found that at that location (50 m from the tower, indoors), emissions in the flight radio band exceeded the quasi-peak magnitude of the tower signal. During some tests, emissions caused audible noise in the tower's communication system.

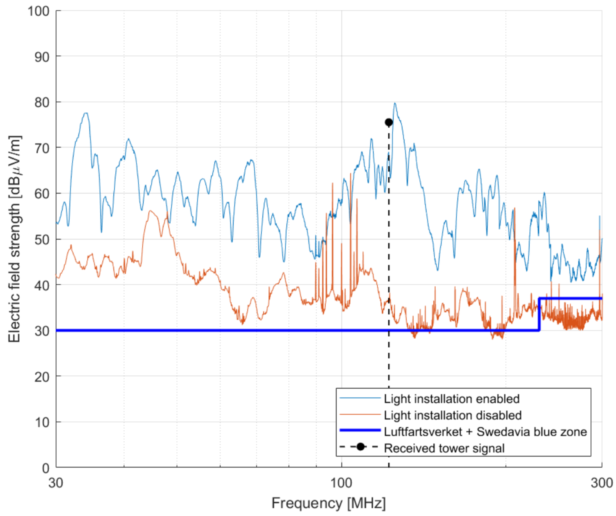

Figure 3: Measured electric field strength inside an airport arrival hall, comparing enabled and disabled light installation. Also the received tower signal and the defined limit at a distance of 10 m. All results specify quasi-peak with 120 kHz RBW except for the towers signal measured with 9 kHz RBW.

6.6 Improvement of Switching Components

Advancements in technology continue to enhance the energy efficiency and switching speed of electronic components. Historically, most electric switching energy has been concentrated in frequency bands below 108 MHz, beneath the flight radio band.

However, as components evolve in both power and frequency capabilities, this energy may shift into higher frequency bands, potentially interfering with CNS systems, an issue predicted in the CENELEC report and already observed in embedded systems [38].

Beyond switching frequency, signal derivatives caused by sharper switching flanks, enabled by improved semiconductor material properties, could further impact emissions in higher frequency ranges. While these emissions can be mitigated by slowing down signal flanks, this approach often compromises signal integrity and efficiency.

One example of a high-power switching system in the airport environment is the GPU. Figure 4 presents measurements up to 200 MHz on a GPU while powering an Airbus A320neo compared to it being disconnected. The measurements have been performed using an Aaronia 20100E antenna connected to a Keysight N9934B signal analyser. Used are both peak and quasi-peak detector to analyse the difference in results.

During operation, emissions were as expected observed in the lower spectrum. However, an increase was also detected in the flight radio band from 109 to 124 MHz. With the peak detector an additional signal was found in the flight radio band at 128 MHz. Results show that the peak and quasi-peak values are approximately 5 dB apart, meaning that the PRF of the emissions is relatively high, something the authors found to be common for switching systems.

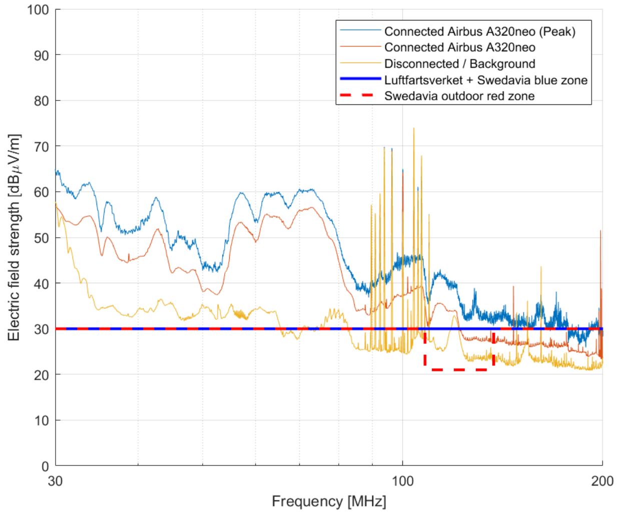

Figure 4: Measured electric field strength from a GPU, both during operation and when disconnected using quasi-peak. Additionally the quasi-peak limits and a measurement during operation with peak detector are visualised. All results specify a distance of 10 m with a 120 kHz RBW

6.7 Outdated Standards / Insufficient Certification

Technology evolves rapidly, and with it, standards and regulatory requirements become increasingly stringent. However, products certified under previous standards may still be in use today. Changes in standards can affect product certification.

For example, before 2020, IEC 61000-6-3 applied to residential, commercial, and light industrial environments. Since then, the standard has been redefined to cover only residential settings, while requirements for commercial and light industrial environments have been transferred to the new IEC 61000-6-8:2020, making IEC 61000-6-3:2020 unsuitable for those industries. Standards typically have transition periods where certification may still be performed with an older standard, but once the transition ends, the latest standard should be applied. Military equipment is exempt from this requirement under certain circumstances.

Companies and individuals introducing products to the European market are responsible for proper certification. While manufacturers may choose the standard they deem most appropriate, this does not guarantee compliance with all regulatory requirements. Insufficient or improper testing may lead to reduced EMC performance, even if a product is classified as certified.

The rise of products imported from outside the EU / EEA has significantly increased the risk of EMC related issues since these products may not always meet European regulatory requirements. Importers must ensure regulatory compliance, but small businesses and private consumers often lack the knowledge or willingness to navigate the complex certification process. When manufacturers provide insufficient or improper documentation, non-compliant products may still reach the European market.

6.8 Ageing of Systems

Products are typically evaluated and certified when new, but their long-term performance remains uncertain. Over time, excessive use, temperature fluctuations, oxidation, and potential damage can push components beyond their original specifications, leading to shifts in their EMC characteristics [39, 40, 41].

Systems in use should always comply with regulations, but regular testing is often lacking. Instead of continuous monitoring, products are typically evaluated only when issues arise.

7 Discussion

The focus of this work is radiated emissions within the 30 to 1000 MHz frequency range. The authors acknowledge that many standards also recommend analysing radiated emissions above 1 GHz, as many airport-related systems operate beyond the 108 MHz operating frequency threshold defined by CISPR standards. Measurements above 1 GHz have also been defined by most aviation and military standards, and additionally, some standards define radiated emissions below 30 MHz. These frequencies are beyond the project's scope and were therefore excluded.

Current emission requirements defined by Swedish airports are based on generic standards and therefore predominantly use the quasi-peak detector. Historically, the quasi-peak detector was preferred for protecting voice and radio communication [22]. Aviation and military applications predominantly use peak detectors, which may provide better visualisation of modern interfering signals. However, since many CNS systems rely on older analog modulation techniques, it can be argued that quasi-peak detection remains advantageous. On the other hand, peak detectors visualise worst-case scenarios and may better represent low PRF signals. Both detectors have advantages and drawbacks, making the ideal choice subject to debate. Additional research is required to identify the most suitable detector for airport applications..

In upcoming phases of this project, the authors will conduct additional measurements, analyse the effects of electromagnetic emissions on aviation systems, and explore the feasibility of applying risk-based EMC principles to airports to understand the possible risks and give advice regarding EMC related airport regulations.

8 Conclusion

While comparing various standards utilising different methods is complex, it can offer insight into the permissible emissions across various types of equipment. Many standards allow deviations from generic requirements depending on the intended function of a product. Based on this, the authors conclude that enforcing current Swedish airport requirements is challenging due to the wide variety of equipment found within an airport vicinity. While emission restrictions are necessary, strict enforcement can be impractical.

The ongoing electrification presents additional challenges. Measurements presented in the paper clearly show that electric aircraft as well as other airport based installations and systems generate electromagnetic emissions that exceed defined limits. Although the paper presents only one case of airport communication system interference, future improvement in semiconductor performance and development of electric systems may shift frequency spectrum of emissions to interference with CNS systems more frequently.

Overall, the findings presented in the paper indicate that further investigations are relevant for standardisation, its implementation, and the impact of emissions from various sources on airport operations.

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