CEPT ECC
Electronic Communications Committee

Addendum to ECC Report 289

Additional studies on the unwanted emissions from Wireless Power Transmission for electric vehicle charging (WPT-EV)

approved 22 May 2026

0 EXECUTIVE SUMMARY

This Addendum to CEPT ECC Report 289 [37] provides

- impact studies of unwanted emissions on radiocommunication services
- more information on technical characteristics of the WPT-EV systems

There has been no consideration of the impact of “dynamic” WPT-EV systems.

This addendum reflects contributions with two different approaches; some are empirical (Annex 1 and Annex 2, based on two field measurements) and some are theoretical. The theoretical studies and calculations presented in this Addendum are assumption-based with several physical phenomena that were not considered. Emission limits or separation distances may require further validation through measurements and deployment scenarios.

Following results of impact studies can be summarised.

1. Amateur service

Field trials in Annex 1 and Annex 2 show no harmful interference to amateur receivers at 3.5 MHz and above which received signals at levels capable of supporting communication at the test locations in the specific environment. Annex 3 (an assessment of the median level of amateur service received signals at a rural location) concludes that the field trials in Annex 1 and Annex 2 have been performed in higher noise environments than a rural environment. However, it was not possible to compare the ambient noise levels of these three scenarios, and therefore to estimate the relative levels of the signals of interest and the interference.

2. Broadcasting

No new studies or measurements, regarding compatibility with Broadcasting, have been completed for this Addendum.

3. Radio astronomy service

For LOFAR-ERIC stations, operating in the 10–90 MHz and 110 MHz–240 MHz range, studies calculated separation distances depending on the WPT-EV spurious emission standard (which was used along it’s spurious emissions limits) of 4.9 km (CIS/B/737/CDV, which was rejected by CISPR), 14.1 km (IEC EN 61980 [7] Class B – residential areas) and 44.3 km (IEC EN 61980 [7] Class A – industrial areas) to protect the RAS bands below 30 MHz. For further information, Figure 9 illustrates the relationship between separation distance and magnetic field strength within RAS bands below 30 MHz.

Furthermore, a dedicated study on spurious emissions above 30 MHz indicates that the calculated separation distance can be as large as 27.2 km.

4. Maritime service

For maritime systems operating in the 283.5-4000 kHz range, calculated separation distances for WPT-EV systems that are assumed to emit spurious emissions according to ERC Recommendation 74-01 are up to 850 m. Several examples show typical natural separation distances of 50 m. Studies showed for locations closer than about 500 m from waterways that maximum emission values between -15 dBµA/m and -35 dBµA/m or values 20 dB below ERC Recommendation 74-01 would protect the maritime service at 50 m distance.

5. Fixed, mobile and maritime service (for military usage)

a) Systems operating in the VLF-LF frequency range

The frequency bands 14-148.5 kHz and 255-526.5 kHz are used for military equipment by NATO in Europe.

For military VLF/LF systems in Annex 5 the following protection criteria at the victim receiver were proposed for military terrestrial systems to avoid interference (reference bandwidth 200 Hz):

- For the VLF band (between 10 and 30 kHz): -25 dBµA/m (H) and 26.5 dBµV/m (E);
- For the LF band (between 30 and 100 kHz): -30 dBµA/m (H) and 21.5 dBµV/m (E).

These values would also apply for maritime systems located in a harbour.

Due to the confidential nature of the victim service, characteristics and a derivation of these values could not be provided.

Calculated separation distances for terrestrial and harbour maritime victim receivers are up to 128 m, based on WPT-EV emissions at IEC 61980 limits [7].

Calculated separation distances for sea maritime victim receivers are up to 2.3 km, based on WPT-EV emissions at IEC 61980 limits. At sea, no WPT-EV devices are expected within 2.3 km distance.

b) Systems operating in the HF frequency range

The band 1606.5-30005 kHz is used for military equipment by NATO in Europe.

The study given in Annex 5 assumes as protection criteria the median level of manmade noise, as defined in Recommendation ITU-R P.372 for different environments. An analysis on introducing WPT-EV with spurious emission levels as defined in ERC Recommendation 74-01 showed that the emissions would exceed these median noise levels within 1.5 MHz and 30 MHz with:

- for city environments 45-54 dB at 5 meters distance;
- for city environments 36-38 dB at 10 meters distance;
- for residential environments 41-42 dB at 10 meters distance.

Based on these assumptions, interference could occur over distances of several hundred meters in HF military receivers operating at the lower threshold of received signal strength.

6. Aeronautical mobile and radionavigation service (for civil aviation usage)

Civil aviation operates two systems below 30 MHz: HF communications and non-directional beacon (NDB). Assuming broadband WPT-EV emission limits at the limit specified in IEC 61980-1 [7] for Class A and Class B systems leads to the following results, obtained for different protection criteria:

- the calculated separation distance to NDB/ADF receivers ranges from 27 m to 228 m for Class B WPT-EV equipment, and from 2.4 km to 65.7 km for Class A WPT-EV equipment;
- the calculated separation distance to HF communication receivers ranges from 3.6 km to 33.5 km for Class B WPT-EV, and more than 100 km for Class A WPT-EV equipment.

Proposed emission values based on I/N criterion of – 6 dB to protect the HF receivers are computed and can be found in Figure 179. Results for the protection of HF ground receiver assume a coordination process could be put in place if the WPT-EV devices were to be deployed closer than 400 m from the HF ground station. For the protection of NDB, emission values have also been derived for WPT-EV assuming the airborne receiver operates at 250 ft (76 m) altitude, and can be found in Figure 178.

7. Information and hypothesis relative to unwanted emission of WPT-EV

For all theoretical studies, it was assumed that the unwanted emissions of WPT-EV systems are continuously distributed across the full frequency band up to 30 MHz and correspond to the maximum limits specified in ERC Recommendation 74-01 [5], ETSI EN 303 417, and IEC 61980 [7], which means that the spurious nature of such emissions (that is, very narrowband harmonics) is not taken into account.

However, results of an EMC test of a series-production device, which used the standardised magnetic resonance design, show the unwanted emissions of a WPT-EV system as follows:

- unwanted emissions below 30 MHz are generally below limits provided in ERC Recommendation 74-01, ETSI EN 303 417 [4] and IEC 61980 [7];
- narrowband peak emissions occur at the fundamental resonance frequency and its harmonics;
- high degree of frequency stability of the fundamental frequency and its harmonics;

- non-WPT-EV-specific emissions (e.g., from power electronics, cables) may be broader in frequency but are not unique to WPT systems;
- the worst-case field strength is limited to a specific direction;
- aggregation effect exists.

No field trials were done which validated the calculated separation distances. Furthermore, it was shown in Annex 4 that unwanted emissions of conductive chargers may already introduce a level of noise which is comparable with the one from WPT-EV chargers. Nevertheless, some general improvement on the unwanted emissions of charging systems would further reduce the risk of interference towards radio services.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
ADF	Automatic Direction Finder
AOC	Aeronautical Operational Control
ARNS	Aeronautical Radionavigation Service
CEPT	European Conference of Postal and Telecommunications Administrations
CES	Comité Électrotechnique Suisse
CPDLC	Controller-Pilot Data Link Communication
DCF77	Time Signal Transmitter located in Frankfurt
DSC	Digital Selective Calling
EAS	Electronic Article Surveillance
ECC	Electronic Communications Committee
ETSI	European Telecommunications Standards Institute
GMDSS	Global Maritime Distress and Safety System
HBA	High-Band Array
HF	High Frequency
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
ISM	Industrial Scientific and Medical
LF	Low Frequency
LOFAR	Low-Frequency Array
MF	Medium Frequency
MIL-STD	Military Standard
NAVDAT	Navigation Data
NAVTEX	Navigational Telex
NDB	Non-Directional Beacon
NJFA	NATO Joint Civil/Military Frequency Agreement
OATS	Open Area Test Site
Pk	Peak
PLC	Power Line Communication; termed in ITU-R Power Line Telecommunications (PLT)
QP	Quasi-Peak

Abbreviation	Explanation
QRN	Q-code according to recommendation UIT-R M.1172 UIT - Indication about disturbance/noise level
QTH	Q-code according to Recommendation UIT-R M.1172 UIT – Coordinates (position) of the transmitting/receiving station
RBW	Resolution BandWidth
RBW	Resolution Bandwidth
RR	Radio Regulations
SDR	Software Defined Radio
SINAD	Signal-to-Noise And Distortion
SPICE	Simulation Program with Integrated Circuits Emphasis
SSB	Single Sideband
USKA	Union Schweizerischer Kurzwellen Amateure (Swiss Union of Short Wave Amateurs)
VDSL	Very high-speed rate digital subscriber line
WGN	White Gaussian Noise
WPT	Wireless Power Transmission
WPT-EV	Wireless Power Transmission for Electric Vehicles

1 INTRODUCTION

ECC Report 289 [37] on "Wireless Power Transmission (WPT) systems for electrical vehicles (EV) operating within 79-90 kHz band" was published in 2019. This Report provides preliminary results on the impact of WPT-EV in 79-90 kHz on radiocommunication services operating below 30 MHz.

Inputs for ECC Report 289 were made for some radiocommunication services (i.e. standard frequency and time signal service, broadcasting service, amateur service, radionavigation service fixed service and mobile service) and a radio application Electronic Article Surveillance (EAS) about the potential impact. At that time limited access to actual WPT-EV systems existed and there were no WPT-EV systems conforming to interoperability standards, which were only beginning to be released in late 2020.

ECC Report 289 covered only WPT-EV static applications. Therefore, this Addendum also covers and describes only WPT-EV static applications. The provided measurements were done for static WPT-EV situations where the vehicle is stationary. Therefore, the dynamic WPT-EV scenarios and configurations where the vehicles are charged in motion (e.g. by charging on lanes, roads and routes) are not covered in this Addendum.

The studies/measurements contained in this Addendum cover the assessment of impact of the unwanted emissions from WPT-EV on military and civil aviation systems, amateur radio, radio astronomy and maritime services.

ECC Report 289, section 6 deals with studies on unwanted emissions of WPT-EV in the spurious emissions domain.

Table 1: Radio systems within the unwanted emissions of WPT-EV

Station	Frequency	Protection bandwidth	Location
MSF (Note 1)	60 kHz	+/-250 Hz	United Kingdom
Amateur	73 kHz		Nationally allocated but cross band communication possible depending on regulation
HBG	75 kHz	+/-250 Hz	Switzerland
LORAN C (Note 2)	90-110 kHz	Over the entire band	World-wide
SRD for car keyless entry system (Note 3)	125 kHz	+/- 4 kHz	World-wide
7DCF49	129.1 kHz	+/-500 Hz	Germany
Broadcasting service	148.5-255 kHz 526.5-1606.5 kHz 525-1705 kHz		Region 1 Regions 1 and 3 Region 2
Amateur	135.7-137.8 kHz	Over the entire band	CEPT allocation
Amateur	160-190 kHz	Over the entire band	Nationally allocated but cross band communication possible depending on regulation

Station	Frequency	Protection bandwidth	Location
Allouis time signal	162 kHz	+/-125 Hz	France
NDB (aeronautical)	200-415 kHz	Over the entire band	Non Directional Beacons (NDBs) are deployed world-wide
Radiolocation (DGPS)	283.5-325 kHz	Over the entire band	World-wide
Amateur	472-479 kHz	Over the entire band	World-wide allocation
Note 1: Standard frequency and time signals are defined by Recommendation ITU-R TF.768. Note 2: This band/system was studied within the out-of-band domain (see section 5 of ECC Report 289). Based on that, the unwanted emission limit is more stringent than the out-of-band domain limit of 42 dBµA/m. This study is not relevant. Note 3: Whilst not in the scope of this Report, it was noted that studies show a significant impact to keyless entry systems from nearby WPT-EV charging stations (< 6 m).			

At the time of developing ECC Report 289 [37], the impact of the unwanted emissions from WPT-EV on radio services was examined with limited input from the WPT-EV industry. Accordingly, concerns were expressed, that some studies may present simplified theoretical worst-case approaches only, not considering system properties developed for series production and established statistical methods to evaluate the probability of radio-frequency interference (RFI) in normal conditions of use by series of production equipment in the electromagnetic environment.

ECC Report 289 concluded that the investigated limits for unwanted emissions of inductive devices (SRDs) and WPT-EV systems emission levels investigated in the Report for radiocommunication services above 150 kHz are significantly lower than the current limits for inductive unwanted emissions of ERC Recommendation 74-01 [5].

ECC Report 289 [37]also calls for “further study” to ensure a low probability of harmful interference to radiocommunication services, including “evaluation of real equipment”, “mitigation techniques” and “other measures to improve WPT-EV systems”, to achieve a level of unwanted emissions sufficient to ensure no harmful interference to radiocommunication services.

After publication of the ECC Report 289, a discussion was initiated about which studies would be needed to complement the Report, especially regarding the unwanted emissions. It was indicated that complementary studies should be done with respect to the impact of unwanted emissions, as follow up action in accordance with the conclusions of ECC Report 289. Observers from the WPT-EV industry were invited to contribute to this work in order to provide information about equipment in development, possible mitigation techniques and other measures that could be considered in the follow up action. WG SE decided that SE24 should take on this complementary study in cooperation with SE21, as necessary.

Reference to standards such as SAE J2954 [39], IEC 61980 [7], CISPR 11, ISO 5474-4 [50] and GB/T 38775 [51] throughout this document is purely informative and does not suggest protection of services in general. In particular, several administrations and stakeholders are of the view that, the RAS, broadcasting service, amateur radio service and military communication systems might not sufficiently protected by the IEC 61980 standard. Protection requirements suitable for medical implants are specified in SAE J2954.

It was noted that calculation methods for EMC purposes and for radio compatibility purposes are different, whereas both claim to be valid (to estimate the necessary level of protection).

2 TECHNICAL PROPERTIES OF WPT-EV

Wireless Power Transmission for Electric Vehicles (WPT-EV) has been studied and continues to be studied for its potential impact on radiocommunication services. In the ITU-R, this type of wireless power transmission (WPT) is labelled as "non-beam WPT". Recommendation ITU-R SM.2110 [55] specifically provides "Guidance on frequency ranges for operation of non-beam wireless power transmission for electric vehicles". Report ITU-R SM.2451 [48] provides "Assessment of impact on radiocommunication services from wireless power transmission for electric vehicle operating below 30 MHz". On occasion, there is a propagated misnomer regarding non-beam WPT in general and specifically regarding WPT-EV. Particularly, it should be noted that non-beam WPT is based on principles of efficient (96-99%)[1] coupling using localised magnetic fields (i.e. near-field reactive) and is not intended as an intended far-field radiator (see Figure 1). One property of this type of coupling is that the energy is transferred or stored locally meaning that the WPT-EV system is optimised to maintain the energy locally in the reactive near-field for transfer to a vehicle with minimal energy leaked beyond the reactive near-field, although this low level of leakage of radiation may not be the primary cause of interference. Indeed, there are other sources of unwanted emissions not related to the coupled magnetic field (e.g. power electronics and other circuitry common to switch-mode power electronics), and these can be dominant. In principle, these same types of localised magnetic fields are used within inductors, transformers, and other components which are common amongst most all electronics. It should be noted that the level of the harmonics, which could be primary contributors to potential interference issues, will generally be related to the power level of the fundamental. Accordingly, it should be noted that the interference potential of non-beam WPT-EV systems in the range above 150 kHz may not primarily caused by the fact that wireless power transmission is present at a fundamental frequency in the range of 79-90 kHz.

Several standards, such as SAE J2954 [21], the IEC 61980 [7] series, ISO 19363 [62], ISO 5474-4 [50] and GB/T 38775 [63], are currently available for WPT-EV system interoperability and conformance requirements. All of these standards have important commonalities that allow characterisation of a WPT-EV system. In particular, WPT-EV systems based on the aforementioned standards:

- Use near-field magnetic resonance to transfer energy wirelessly between a loosely coupled ground coil assembly and a vehicle coil assembly by means of magnetic field coupling;
- Utilize filtered sinusoidal currents in the ground assembly coil to generate a local magnetic field for transferring power;
- Have an efficiency from AC mains input to DC output greater than 80% though measured values have shown typical efficiencies at ~90%;
- Operate in the range of 79-90 kHz (nominally 85 kHz)[1] but do so at a fixed frequency across the full charging cycle of a vehicle;
- Do not modulate the wireless energy between the ground and vehicle coil assemblies in any way for communication but instead utilize out-of-band wireless communications (such as Wi-Fi), which follow well-established global radio requirements;
- Meet set requirements for human and Cardiac Implantable Electronic Device CIED EMF safety based on ICNIRP 2010 guidelines [19] for human exposure (for frequencies below 100 kHz) and ISO 14117 guidelines [20] for CIED magnetic field compatibility;
- Use power levels starting from 3.7 kW (WPT1 power class) and up to 11.1 kW (WPT3 power class);
- Meet minimum alignment tolerance requirements as +/- 75 mm in the direction of vehicle travel and +/- 100 mm in the lateral direction;
- Meet requirements for foreign object detection to prevent unsafe metallic object heating;
- Compatibility between WPT-EV and Ultra Low Powered Active Medical Implants/Peripherals - ULP-AMI/ULP-AMI-P communications operating in the 9-315 kHz range, per ERC Recommendation 70-03, Annex 12a [60] and ETSI EN 302 195 [61], when a minimum separation distance of at least 2 meters is preserved between WPT-EV charging coils and an active ULP-AMI/ULP-AMI-P communication session (e.g. in a hospital, medical clinic, or inside a patient's home).

An example block diagram of a standardised WPT-EV system is given in Figure 1.

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[1] "As the result, the industry concluded that 79-90 kHz (so-called 85 kHz band) is the most appropriate selection for those applications." Source: Report ITU-R SM.2303, section 2.4.

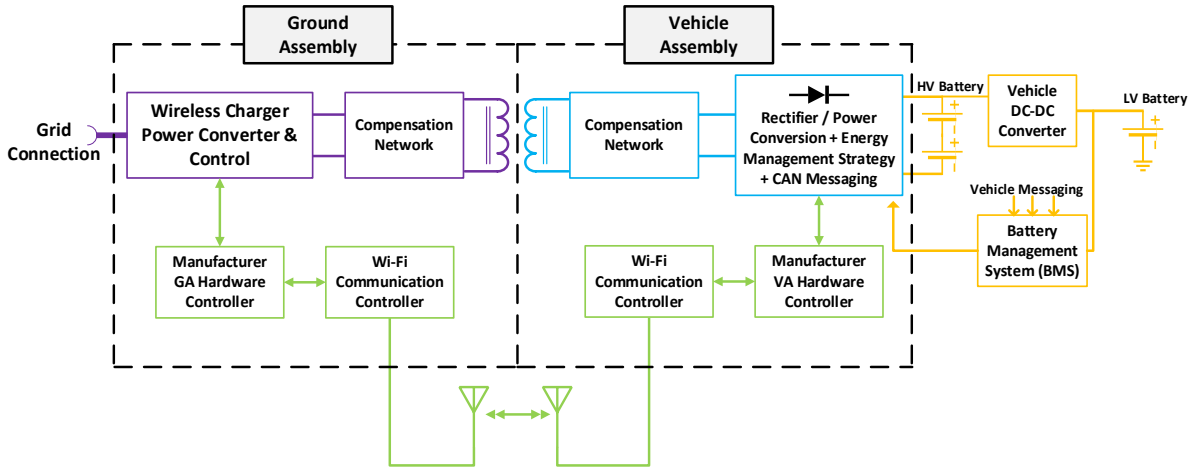


Figure 1: Block diagram of typical WPT-EV system from SDOs

For clearer understanding, the block diagram of a conductive EV charger and a WPT-EV charger are shown below. The related measured efficiencies of these systems are also shown.

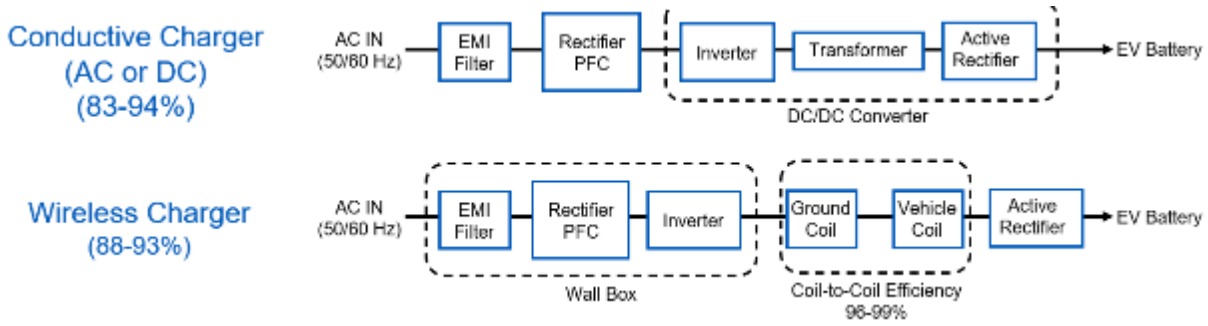


Figure 2: Comparative Block Diagrams for Conductive and WPT-EV Chargers

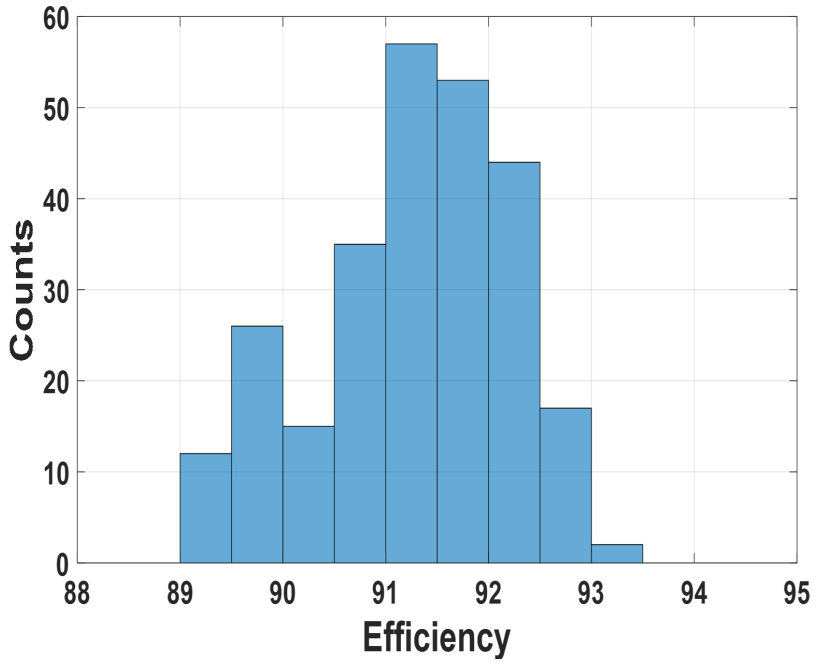


Figure 3: Measured Efficiency of WPT-EV (counts represent measurements in different positional and battery conditions)

Report ITU-R SM.2303 [47], section 2.4 "Electric vehicle" states that "In most use cases for passenger vehicles of the personal use, 3.3 kW, 7.7 kW or 11 kW. However, some users for the public use want to charge quickly or their car for specific use purpose may need much bigger power. 22 kW or higher power range is also taken in consideration for passenger vehicles today. In use cases for heavy duty vehicles, the initial 75 kW equivalent charging power may be required. The 100 kW or higher power range are also taken into consideration."

3 POSSIBLE MITIGATION TECHNIQUES TO REDUCE THE IMPACT OF WPT-EV UNWANTED EMISSIONS

In order to indicate possible mitigation techniques to reduce the impact of WPT-EV unwanted emissions on radio services, it is important to understand possible sources of emissions from WPT-EV systems. In general, unwanted emissions are caused either by differential currents or common-mode currents present in the system.

Common-mode currents are typically unrelated to the power transfer itself will often dominate unwanted emissions[2].

Differential-mode currents are not directly related to the wireless power transmission but could be present in emissions measurements.

Well-known techniques exist to mitigate these emissions. In the instance of WPT-EV, more advanced techniques can be applied.

Differential-mode emissions directly related to the current in the primary (ground assembly) coil depend on the current characteristics in the coil as well as the geometry, ferrite, and other system characteristics. WPT-EV systems utilize magnetic resonance, which inherently filters harmonics from the switch-mode H-bridge power converter. Aforementioned standards (such as SAE J2954 [21]) provide recommended and standardised system architecture to allow such filtering.

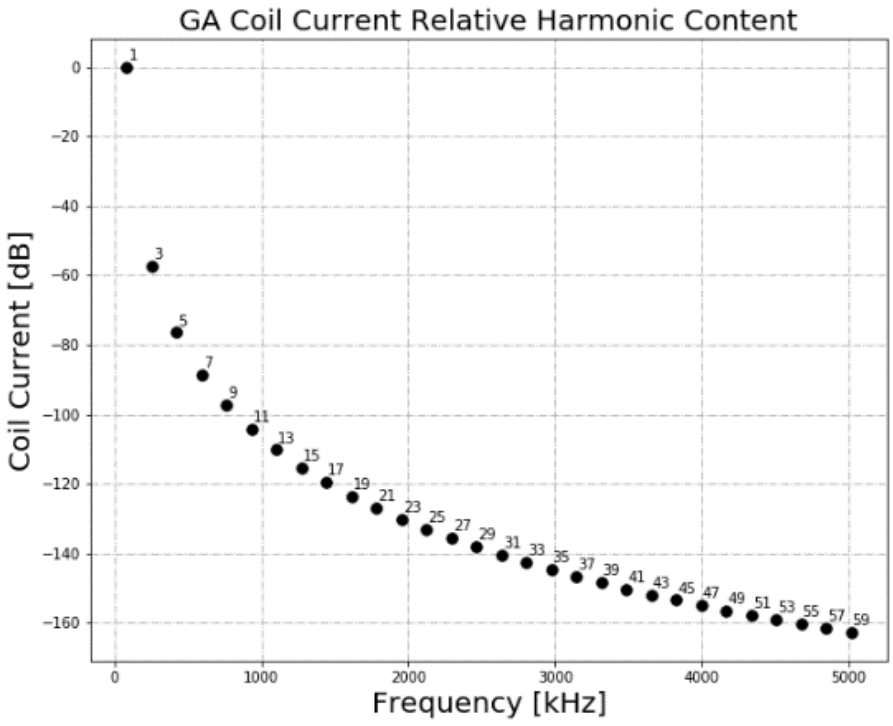


Figure 4: Calculated relative harmonic content of WPT-EV coil current in ground assembly

[2] Introduction to Electromagnetic Compatibility, Clayton R. Paul, John Wiley & Sons, Inc., 1992 states on page 301, "… *a small common-mode current can produce the same level of radiated electric field as a much larger value of differential-mode current.* In short, *common-mode currents have a much higher potential for producing radiated emissions than do differential-mode currents! … the predominant mechanisms for producing radiated electric fields in practical products are the common-mode currents on the conductors!*" (italics and punctation as shown in the text)

Additionally, SPICE simulations show expected time domain and frequency domain plots of the current in the ground assembly coil.

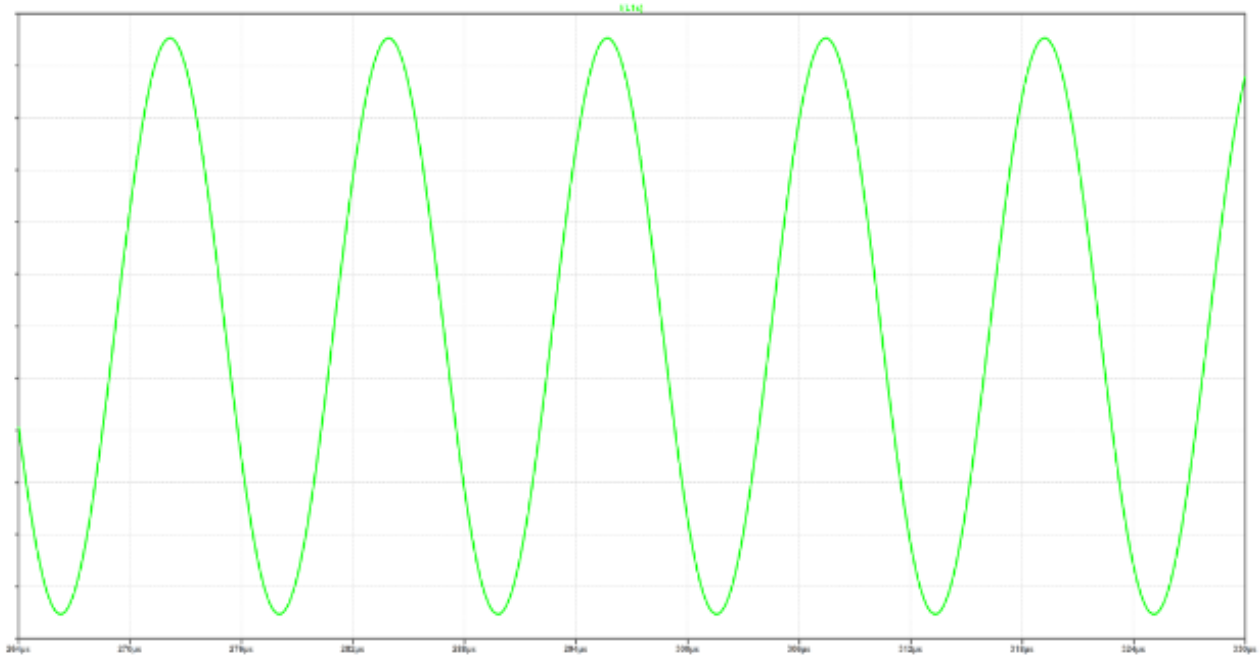


Figure 5: SPICE simulated time-domain current waveform of coil current in WPT-EV ground assembly

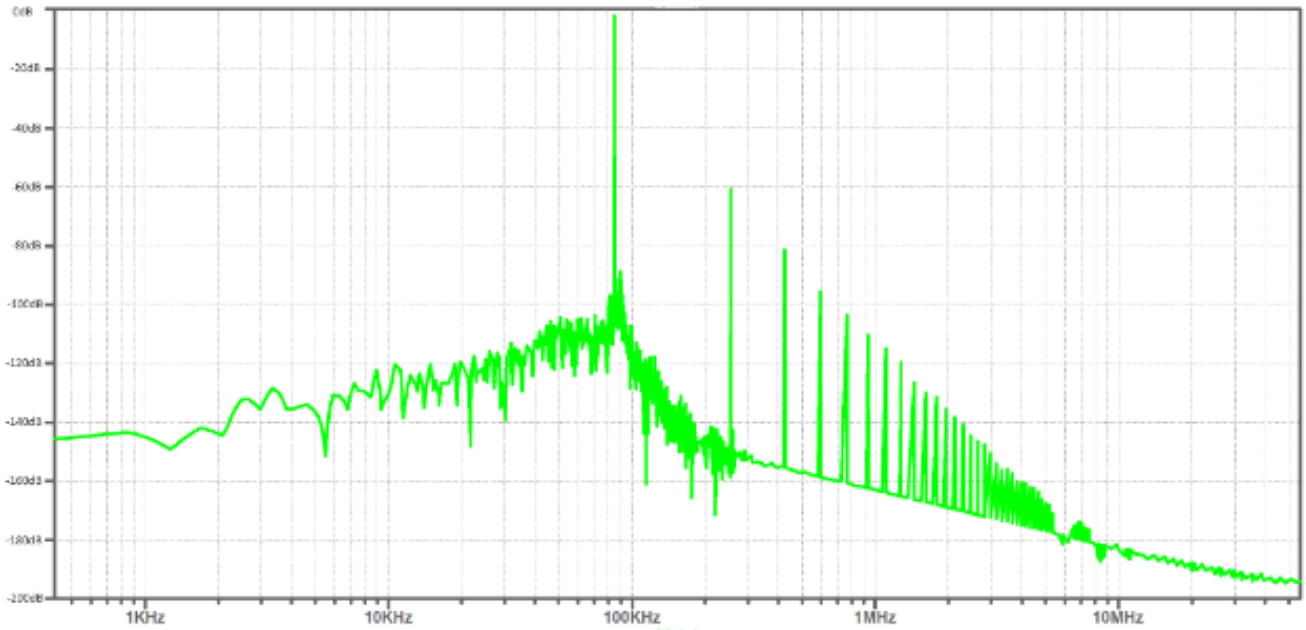


Figure 6: SPICE simulated relative frequency-domain spectrum of coil current in WPT-EV ground assembly

Finally, the resultant coil current was measured using a standard current probe and oscilloscope with the waveform shown below.

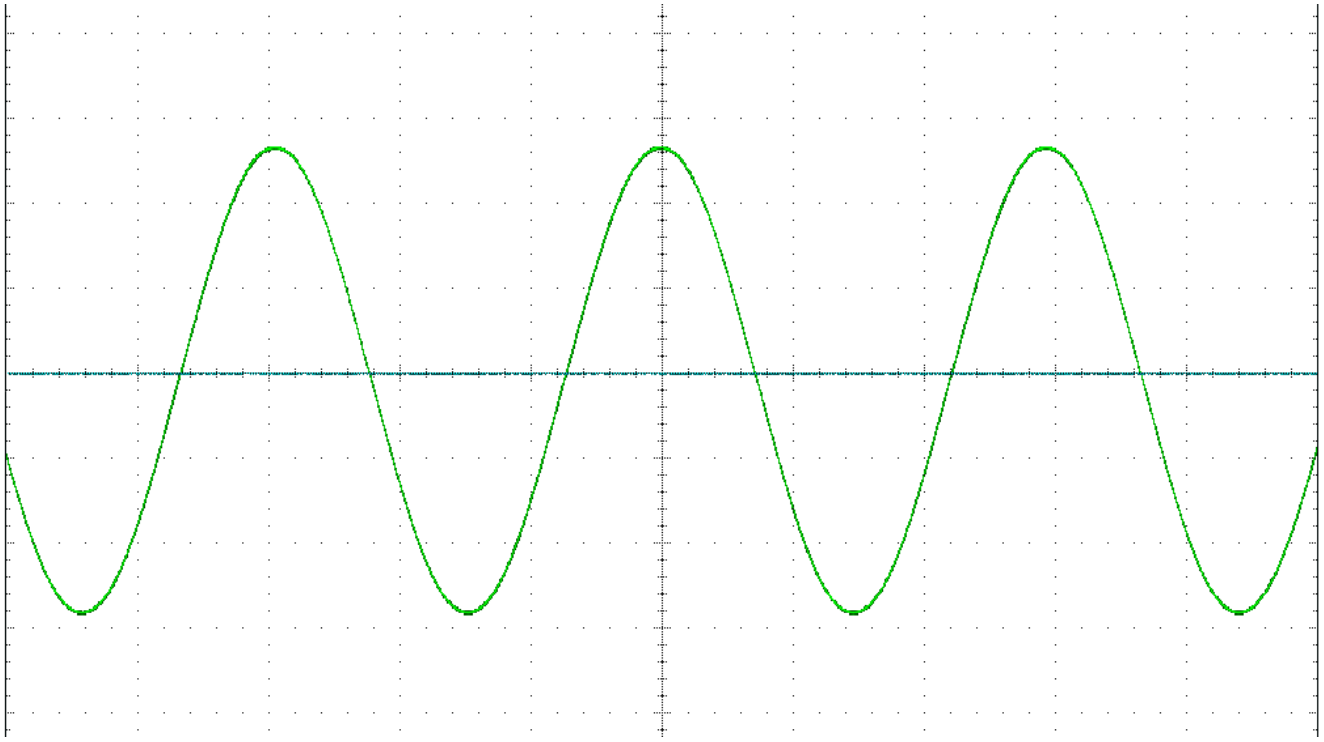


Figure 7: Actual coil current measured in the time-domain with oscilloscope

To ensure appropriate mitigation of potential emissions emanating from the differential-mode emissions in the primary (ground assembly) coil, manufacturers may consider the following:

- Utilize inductors and capacitors with high quality factors and high self-resonance in the impedance matching network (compensation network);
- Maintain identical or similar geometries, networks and electronics for the primary (ground assembly) magnetics used to couple to the secondary (vehicle assembly);
- Maintain identical or similar geometries, networks and electronics for the secondary (vehicle assembly) magnetics used to receive the energy from the primary (ground assembly).

Report ITU-R SM.2451 [48] concludes that "Limits on radiation and mitigation techniques, as well as other relevant matters, including guidance to administrations, are best promulgated through ITU-R Recommendations and Reports, supplemented by further studies and documentation as considered necessary". Following Report ITU-R SM.2451 [48], section 4 "Summary of the studies on the impact of WPT-EV on radiocommunication services", these WPT-EV measures are significant: enhanced stability and purity; a harmonised, tightly tolerance frequency of operation; low phase noise and noise sidebands.

4 COMPATIBILITY STUDIES WITH THE RADIO ASTRONOMY SERVICE

4.1 COMPATIBLITY STUDIES WITH RADIO ASTRONOMY SERVICE BELOW 30 MHZ

4.1.1 Overview of European Radio Astronomy facilities operating in the low frequency radio astronomy bands

The Low-Frequency Array (LOFAR) telescope (www.lofar.org), is mainly situated in the Netherlands and operated by ASTRON as part of a broader pan-European network. LOFAR enables exploration of cosmic phenomena, including cosmic rays, black holes and the primordial universe. Unlike traditional telescopes, LOFAR adopts an approach comprising numerous antennas (around 70000) distributed across Europe. In particular, LOFAR operates at radio frequencies from 10 to 90 MHz (Low Band Antennas, LBA) and 110 to 240 MHz (High Band Antennas, HBA). This distributed architecture includes a total of 52 stations (interactive map: https://www.astron.nl/lofartools/lofarmap.htmlhere), each contributing to a vast network that collectively synthesises signals to create a virtual aperture. By taking advantage of this distributed network, LOFAR achieves high imaging resolution and greater sensitivity, significantly improving its observation capabilities. Recently the LOFAR radio telescope has acquired the designation of European Research Infrastructure Consortium (ERIC). Designed to optimize infrastructure management and consolidate Europe's global leadership in the field, this legal entity was established by Decision No. 2023/2881 of the European Commission on 20 December 2023 [1]. In 2025 LOFAR was upgraded: LOFAR2.0, allows the simultaneous use of all LBA and HBA antennas, improve sensitivity and expand the field of view.



Figure 8: Geographical distribution of the existing LOFAR stations in Europe (Source: ASTRON)

As part of the LOFAR network, it is important to highlight NenuFAR (New Extension in Nançay Upgrading LOFAR), located in Nançay, France. This 2000-antenna phased-array telescope, with a 3 km baseline, with operating frequency from 10 to 85 MHz, has been officially designated as a pathfinder for the future Square Kilometre Array (SKA), which is set to become the world's largest radio telescope. The site also hosts the Nançay Decameter Array (NDA), which consists of 144 helicoidal antennas operating in the frequency range 10-120 MHz.

The list of current radio telescopes in CEPT countries operating within frequency ranges under study is provided in Table 2 (this table is not to be considered exhaustive). Due to the dense concentration of, stations in the Netherlands, Dutch LOFAR stations are listed separately in Annex 8.

Table 2: List of RAS stations belonging to the LOFAR-ERIC network in CEPT countries

Observatory	Name	Country	Latitude (N)	Longitude (E)
LOFAR, core stations, Exloo	CSxx (24 core stations, see Table 14)	Netherlands	52°54'32"	6°52'08"
LOFAR, remote stations (distributed)	RSxx (14 remote stations, see Table 14)		see Table 14	
Rozhen	-	Bulgaria	41°42'00"	24°44'44"
Nançay	FR606	France	47°22'32"	02°11'33"
Effelsberg	DE601	Germany	50°31'29"	06°53'01"
Unterweilenbach	DE602		48°30'05"	11°17'16"
Tautenburg	DE603		50°58'48"	11°42'40"
Bornim	DE604		52°26'17"	13°00'58"
Jülich	DE605		50°53'49"	6°25'26"
Norderstedt	DE609		53°41'54"	9°58'09"
Medicina	-	Italy	44°31'08"	11°39'01"
Birr	IE613	Ireland	53°05'42"	-7°55'19"
Irbene	LV614	Latvia	57°33'27"	21°51'17"
Borowiec	PL610	Poland	52°16'33"	17°04'25"
Lazy	PL611		49°57'53"	20°29'23"
Baldy	PL612		53°35'37"	20°35'21"
Onsala	SE607	Sweden	57°23'35"	11°55'04"
Chilbolton	UK608	United Kingdom	51°08'38"	-1°26'03"

4.2 USE OF THE BAND BY RAS BELOW 30 MHZ

Below 30 MHz, RAS has two allocations. The RAS bands considered in this study are sourced from the ECA Table [2].

Table 3: RAS frequency allocation and usage below 30 MHz according to the ECA Table

RAS frequency bands	Type of RAS observation
13.360-13.410 MHz	Continuum
25.550-25.670 MHz	Continuum

Observations in the lower part of the spectrum allow for investigating the physics of the Sun and its impact on Earth's magnetosphere, also known as "space weather". There is interest in conducting imaging radio campaigns to catalogue the sky map using low-frequency bands. Another main science driver is exoplanets, as they exhibit a very steep spectrum above a certain value, making low frequencies more sensitive than even HBA frequencies. This part of the spectrum is also used to observe and study pulsars (see LOFAR White Paper here).

4.3 WPT-EV PARAMETERS

The unwanted emission produced by WPT-EV systems can vary depending on the application. This analysis focuses on emission limits reported in various standards but does not consider actual characteristics emissions of a WPT-EV system. ETSI EN 303 417 [4] addresses WPT systems, including WPT-EV, and sets a magnetic field limit in transmit mode as -3.5 dBµA/m within the 10-30 MHz frequency range. Table 4 shows the radiated magnetic field strength below 30 MHz as defined in ETSI EN 303 417 which aligns with ERC Recommendation 74-01, table 6 [5]. Additionally, the study incorporates the CISPR B standard, in particular CISPR 11 Class B CIS/B/737/CDV [6], which sets the limit of magnetic field at -10 dBµA/m at 10 m. It is to be noted that Class B CIS/B/737/CDV was rejected in CISPR. Furthermore, the IEC EN 61980 Class A and Class B are also considered [7]. Figure 9 illustrates this, with the RAS bands marked with dashed red lines for IEC EN 61980 Class B. Table 4 summarises the applied standards and their corresponding limits within the relevant RAS bands. It is assumed that the emissions emanating from such a WPT-EV system are at the proposed limit and at the relevant frequency of the victim receiver, considering single-entry worst-case studies.

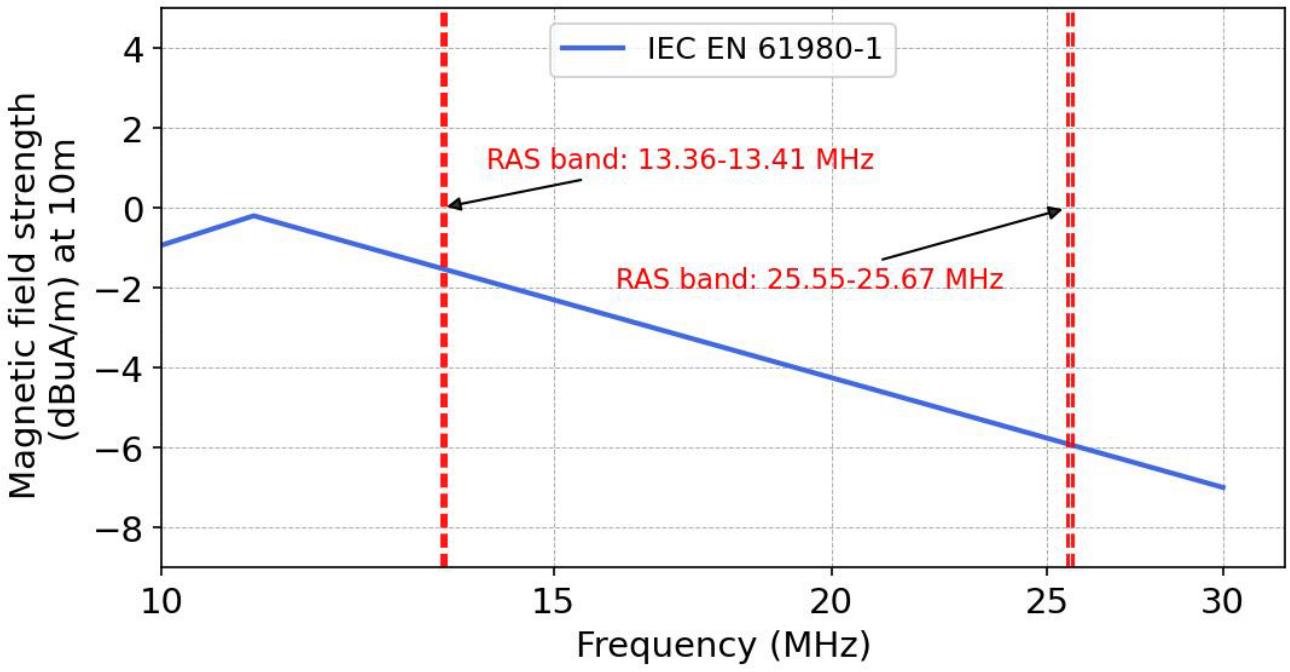


Figure 9: Emission limit according to IEC EN 61980-1 [7] Class B standard for the frequency range 10-30 MHz

Table 4: Radiated WPT-EV emission levels in the 10-30 MHz range considered in this study

Standard	Note	Magnetic field strength at 10 m
ERC Recommendation 74-01, annex 2 [5]	Mode: Operating (Note 1)	-3.5 dBµA/m
	Mode: Standby (Note 1)	-25 dBµA/m
CISPR	Class B CIS/B/737/CDV (Note 2)	-10 dBµA/m
IEC EN 61980-1 [7]	Class A	freq. 13.38 MHz: ~ 18.5 dBµA/m
		freq. 25.61 MHz: ~ 8.1 dBµA/m
IEC EN 61980-1 [7]	Class B	freq. 13.38 MHz: -1.4 dBµA/m
		freq. 25.61 MHz: -5.8 dBµA/m
Note 1: "Operating" means mode 2, 3 and 4 "Standby" means mode 1 according to ETSI EN 303 417, table 2 [4] Note 2: Class B CIS/B/737/CDV was rejected in CISPR		

4.4 RAS PARAMETERS

Protection criteria for RAS[3] are defined in Recommendation ITU-R RA.769-2 [3] and summarised in Table 5 for convenience.

Table 5: Radio astronomy technical parameter

System Parameter	Value	Remarks
Integration time	2000 s	According to Recommendation ITU-R RA.769-2
Side lobe gain, G_r	0 dBi	According to Recommendation ITU-R RA.769-2, only side lobe receptions need to be considered
Threshold interference power flux density level, PFD_{limit}	13.385 MHz: -201 dBW/m2	According to Recommendation ITU-R RA.769-2, table 1 for continuum observations
	25.610 MHz: -199 dBW/m2	
Assumed bandwidth	13.385 MHz: 50 kHz	According to Recommendation ITU-R RA.769-2, table 1 for continuum observations
	25.610 MHz: 120 kHz	
Electric field strength, E_{limit}	13.385 MHz: -54.87 dBµV/m	Derived from Recommendation ITU-R RA.769-2: Table 1 for continuum observation. Assumption of free space propagation and far-field condition ($E_{rms} = \sqrt{PFD \cdot Z_0}$, $Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 376.73\ \Omega$) (see Report ITU-R RA.2131-0 [77])
	25.610 MHz: -52.55 dBµV/m	

[3] Recommendations RA.517 'Protection of the radio astronomy service from transmitters operating in adjacent bands' and RA.611 'Protection of the radio astronomy service from spurious emissions' are significant.

4.5 DETAILS AND OUTCOME OF STUDIES

4.5.1 Below 30 MHz

The frequency range below 30 MHz causes signal propagation to differ from free-space conditions. This is because ground wave propagation is dominant and signals tend to follow the curvature of the Earth, with significant interaction with the ground surface. The propagation is modelled according to the methodology of Recommendation ITU-R SM.2028-0 [10], which is also described in ERC Report 69 [9] and is based on data from Recommendation ITU-R P.368 [8]. This model is appropriate for propagation attenuation of signals from 10 kHz up to 30 MHz. Ground wave propagation was considered given that RAS sites are ground-based, with typical land properties ($\sigma = 3\ mS/m,\ \varepsilon_r = 22$) see ITU Handbook [11] and the protection criteria are derived from Recommendation ITU-R RA.769-2 [3] (see Table 5). For further details on ground wave propagation, see [11]. All calculations assume far field conditions, which is reasonable given the frequency bands of interest. For simplicity, the centre frequencies of RAS bands involved (13.385 MHz and 25.610 MHz) are used as references in the calculation. According to ERC Report 69 [9] and Recommendation ITU-R SM.2028 [10], the bandwidth ratio BWR is 0 dB, as the interfering signal's reference bandwidth (typically around 10 kHz) is smaller than the reference bandwidths of RAS according to ITU-R RA.769-2 [3], which are reported in Table 5.

Table 6 and Table 7 summarise the scenarios studied and the corresponding level of emission. The procedure to determine the separation distance is shown further. Initially, the magnetic dipole is defined either coaxial or coplanar as described in [9] and [10]. For this study the magnetic dipole is coplanar also according to expected scenario. Then, the Effective Radiated Power (ERP) is computed as follows:

$$ERP = \frac{\mu_0 c}{6\pi}\frac{m^2}{\lambda_r^4} = 20\frac{m^2}{\lambda_r^4} \quad (W)$$

where:

- λ_r is the radian wavelength also known also as wavenumber ($\lambda/2\pi$).

The Electric field strength limits (E_{limit}) are derived (see Table 5). The acceptable interference level (E_{int}) is computed using the formulae and data from [9] and [10].

$$E_{int} = E_{asympntote,40}E_{asyntote,40} + ERP_{dBkW} \quad (dB\mu V/m)$$

Based on these assumptions, the interfering signal is subjected to an attenuation of 40 dB/decade. The separation distance between the transmitter and the RAS station is calculated in accordance with Recommendation ITU-R SM.2028 [10] and Recommendation ITU-R P.368 [8], taking into account ground wave propagation.

$$d_{Tx-RAS} = 1000 \cdot 10^{\frac{E_{int}-E_{limit}}{40}} \quad (m)$$

Table 6: Separation distances derived from ERC Recommendation 74-01, annex 2 spurious emission levels between 10 and 30 MHz

RAS band	Radiated emission limit, Hm	ERP	Separation Distance
13.36-13.41 MHz	Operating mode: -3.5 dBµA/m at 10 m	-98.0 dBkW	12.5 km
	Standby mode: -25 dBµA/m at 10 m	-119.5 dBkW	3.6 km
25.55-25.67 MHz	Operating mode: -3.5 dBµA/m at 10 m	-98.4 dBkW	7.2 km
	Standby mode: -25 dBµA/m at 10 m	-119.9 dBkW	2.1 km

Table 7: Separation distances derived from IEC EN 61980 and CISPR 11 CIS/B/737/CDV spurious radiated emission levels

RAS band	Reference	Radiated emission limit, Hm	ERP	Separation Distance
13.36-13.41 MHz	IEC EN 61980, Class A [7]	~ 18.5 dBµA/m at 10 m	-76.0 dBkW	44.3 km
25.55-25.67 MHz		~ 8.1 dBµA/m at 10 m	-52.6 dBkW	14.0 km
13.36-13.41 MHz	IEC EN 61980, Class B [7]	-1.4 dBµA/m at 10 m	-95.9 dBkW	14.1 km
25.55-25.67 MHz		-5.8 dBµA/m at 10 m	-100.7 dBkW	6.3 km
13.36-13.41 MHz	CISPR 11 class B CIS/B/737/CDV (Table C and F) (Note 1)	-10 dBµA/m at 10 m	-104.5 dBkW	8.6 km
25.55-25.67 MHz			-104.9 dBkW	4.9 km
Note 1: Class B CIS/B/737/CDV was rejected in CISPR				

The distance calculation is based on the EMC limits of IEC 61980-1 and ETSI EN 303 417 [4]. These limits are identical to the general EMC limits of CISPR-11 for all ISM RF devices and ERC/REC 74-01 for short range inductive devices.

The results of the studies below 30 MHz indicate the separation distance required to protect the LOFAR stations. The required separation distances to protect RAS for WPT-EV operation range from 4.9 km up to 44.3 km depending on the radiated emission.

For the sake of completeness, the below figure shows the results achieved based on the referenced standards. It also illustrates the relationship between the separation distance (WPT-EV and RAS) and the WPT-EV emission expressed in terms of magnetic field strength.

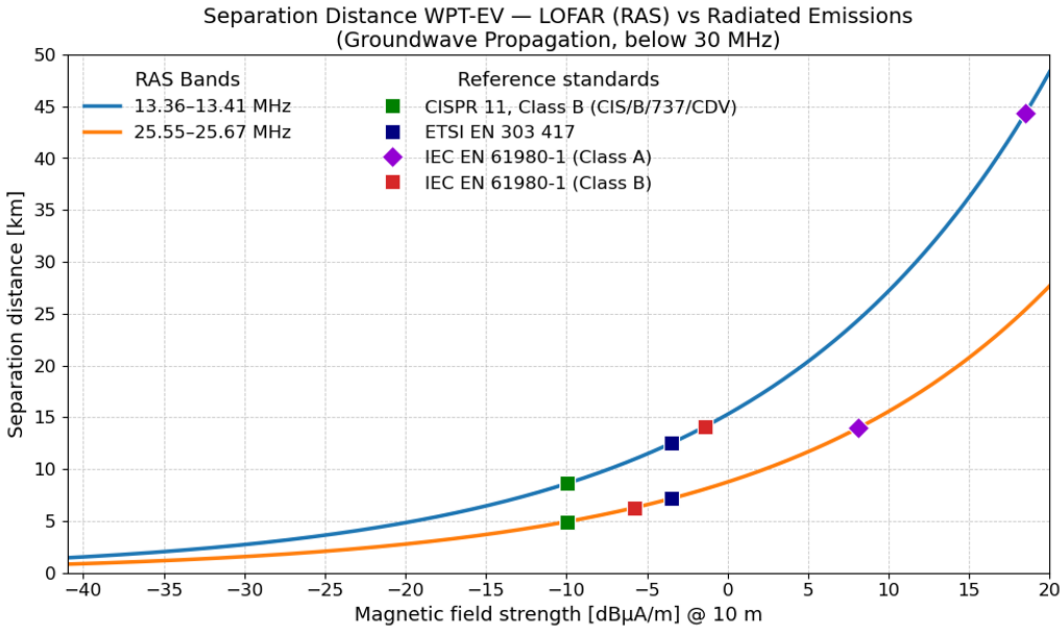


Figure 10: Separation distances between WPT-EV in operating mode and RAS (below 30 MHz) WPT spurious and harmonics emissions above 30 MHz for radio astronomy

This study assumes that the WPT-EV systems, could generate spurious emissions and harmonics extending above 30 MHz, potentially causing interference in bands allocated to RAS. Spectrum measurements presented in section 2 and Annex 8 showed that harmonics of the WPT-EV magnetic field fall below the noise level of that measurement equipment above 1 MHz. However, the RAS protection criteria specified in ITU-R RA.769-2 [3] are well below the ambient noise floor as defined in Recommendation ITU-R P.372-17.

Although these bands are already shared with various services, many sensitive RAS observations are still feasible. Consequently, this study indicates that WPT-EV systems could impact frequencies also above 30 MHz.

RAS uses the frequency allocations shown in the below table. Bands considered in this study are sourced from the ECA Table [2]. The analysis focuses on the frequency range up to 1 GHz, as indicated in ERC Recommendation 74-01, table 1 [5].

Table 8: RAS frequency allocation usage between 30 MHz and 1 GHz according to the ECA Table

RAS frequency bands	Type of RAS Observation
37.5-38.25 MHz	Continuum
70.45-74.8 MHz	Continuum
150.05-153 MHz	Continuum
322-328.6 MHz	Continuum, spectral line and VLBI
406.1-410 MHz	Continuum, VLBI
606-614 MHz	Continuum, VLBI

4.5.1.1 Site-generic study

In the following study, the propagation model outlined in Recommendation ITU-R P.452-17 [12] is valid from 100 MHz and above, therefore this study focuses exclusively on radio spectrum frequencies above 100 MHz. The performed analysis is restricted to generic site with smooth earth assumption. Furthermore, no clutter was considered as the analysis is limited to single-entry worst-case scenario. Table 9 and Table 10 show the technical parameters of WTP and RAS respectively.

The protection criteria for RAS are outlined in Recommendation ITU-R RA.769-2 [3], which are based on an integration time of 2000 seconds.

Table 9: WPT-EV technical parameters

System Parameter	Value	Remarks
Antenna height of WPT-EV, h_{WPT}	0.05 m	WPT-EV systems are typically situated underground. For simplicity, a low height is considered.
WPT spurious emission (operating mode), P_{TX}	151.525 MHz: -36 dBm	According to ETSI EN 303 417 [4]
	325.3 MHz: -36 dBm	
	408.05 MHz: -36 dBm	
	611 MHz: -54 dBm	

Table 10: Radio astronomy technical parameters

System Parameter	Value	Remarks
Integration time	2000 s	According to Recommendation ITU-R RA.769-2
Data loss	2%	According to Recommendation ITU-R RA.1513-2 [75]
Side lobe gain, G_r	0 dBi	According to Recommendation ITU-R RA.769-2, only side lobe receptions need to be considered
RAS antenna height, h_{RAS}	30 m	
Threshold interference levels	151.525 MHz: -199 dBW	According to Recommendation ITU-R RA.769-2, table 1 for continuum observations
	325.3 MHz: -201 dBW	
	408.05 MHz: -203 dBW	
	611 MHz: -202 dBW	

According to the assumptions previously listed, the separation distances are reported in Table 11. Since almost all RAS stations observe above 30 MHz, these separation distances should be applicable to all RAS stations. The study reveals that the exclusion zones are particularly large, ranging from a few kilometres to several tens of kilometres.

Table 11: Separation distance according to spurious emission from ETSI EN 303 417 [4] for WPT-EV between 30 MHz and 1 GHz

RAS band	WPT-EV state	Spurious emission	Separation Distance according to Recommendation ITU-R P.452 [15]
150.05-153 MHz	Operating mode	250 nW (-36 dBm)	27.2 km
	Standby mode	2 nW (-57 dBm)	2.5 km
322-328.6 MHz	Operating mode	250 nW (-36 dBm)	10.6 km
	Standby mode	2 nW (-57 dBm)	0.96 km
406.1-410 MHz	Operating mode	250 nW (-36 dBm)	9.5 km
	Standby mode	2 nW (-57 dBm)	0.9 km
606-614 MHz	Operating mode	4 nW (-54 dBm)	1 km
	Standby mode	2 nW (-57 dBm)	4.1 km

4.5.1.2 *Site specific study of LOFAR Core station*

The primary RAS allocated band of 150.05-153 MHz is within the operational range of LOFAR. The impact of WPT-EV on RAS is studied, considering the terrain signal attenuation above 30 MHz. The transmitted power is assumed to be -36 dBm as specified in ETSI EN 303 417 [4]. The propagation model used is in Recommendation ITU-R P.452 [12] with a time percentage of 2% according to ITU-R RA.1513-2 [75]. The protection criteria are based on ITU-R RA.769-2, which defines a power threshold of -199 dBW (continuum observations). It is assumed a RAS antenna height of 1 m, while WPT-EV height of 0.05 m. The LOFAR core

station (see Table 2) is chosen as the example site, with Lidar Terrain Data [70]. Figure 13 illustrates the calculated separation distance to protect the RAS station from WPT-EV radiated spurious emissions. The resulting separation distance is around 20 km, which is in accordance with the results of the previous generic study above 30 MHz in which 27.2 km was derived. It should be noted that, there are obstacles to the WPT-EV signal, "of which additional attenuating effect has not been modelled in this study", and therefore interference may be lower.

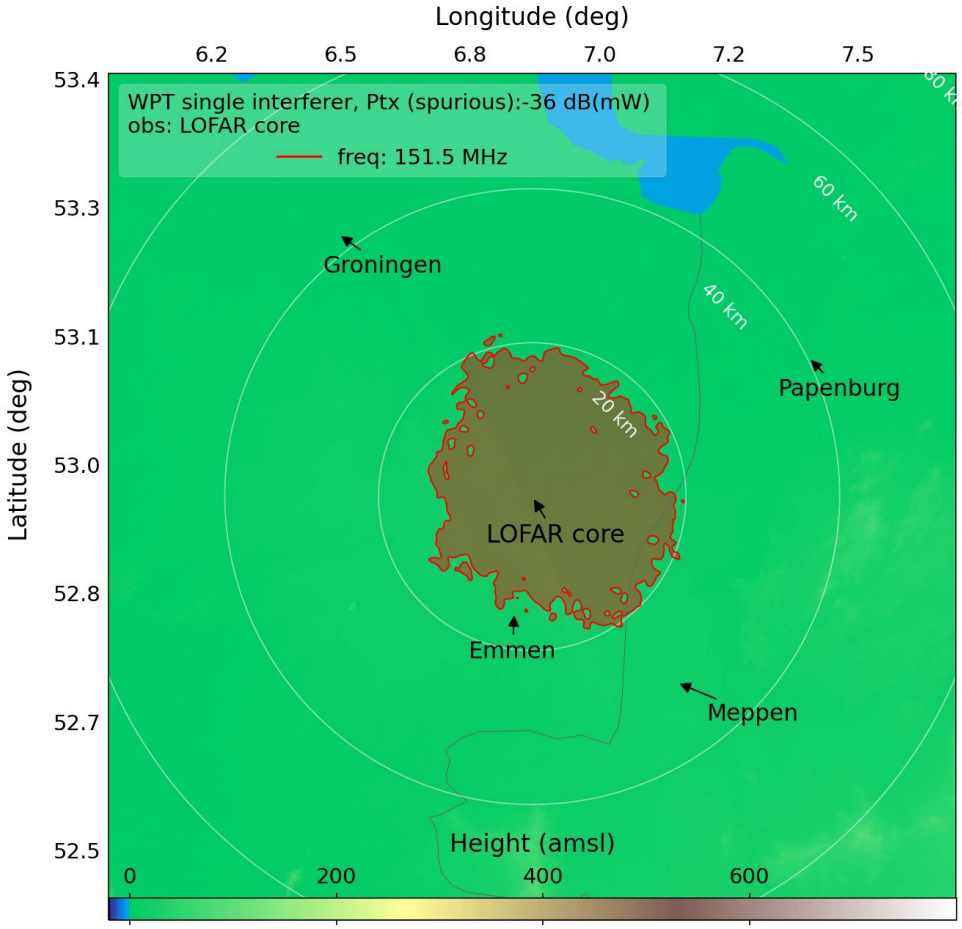


Figure 11: Separation distance from WPT-EV to LOFAR core station at 151.5 MHz

Table 13 summarises the scenarios studied and the corresponding level of emission. The procedure to determine the separation distance is shown further. Initially, the magnetic dipole is defined either coaxial or coplanar, as described in [9] and [10]. For this study the magnetic dipole is coplanar also according to expected scenario. Then, the Effective Radiated Power (ERP) is computed as follows:

$$ERP = \frac{\mu_0 c}{6\pi}\frac{m^2}{\lambda_r^4} = 20\frac{m^2}{\lambda_r^4} \quad (W)$$

where:

- λ_r is the radian wavelength also known also as wavenumber ($\lambda/2\pi$).

The Electric field strength limits (E_{limit}) are derived (see Table 5). The acceptable interference level (E_{int}) is computed using the formulae and data from [9] and [10].

$$E_{int} = E_{asympntote,40}E_{asyntote,40} + ERP_{dBkW} \quad (dB\mu V/m)$$

Based on these assumptions, the interfering signal is subjected to an attenuation of 40 dB/decade. The separation distance between the transmitter and the RAS station is calculated in accordance with

Recommendation ITU-R SM.2028 [10] and Recommendation ITU-R P.368 [8], taking into account ground wave propagation.

$$d_{Tx-RAS} = 1000 \cdot 10^{\frac{E_{int}-E_{limit}}{40}} \quad (m)$$

Table 12: Separation distances derived from ERC Recommendation 74-01, annex 2 spurious emission levels between 10 and 30 MHz

RAS band	Radiated emission limit, Hm	ERP	Separation Distance
13.36-13.41 MHz	Operating mode: -3.5 dBµA/m at 10 m	-98.0 dBkW	12.5 km
	Standby mode: -25 dBµA/m at 10 m	-119.5 dBkW	3.6 km
25.55-25.67 MHz	Operating mode: -3.5 dBµA/m at 10 m	-98.4 dBkW	7.2 km
	Standby mode: -25 dBµA/m at 10 m	-119.9 dBkW	2.1 km

Table 13: Separation distances derived from IEC EN 61980 [8] and CISPR 11 CIS/B/737/CDV spurious radiated emission levels

RAS band	Reference	Radiated emission limit, Hm	ERP	Separation Distance
13.36-13.41 MHz	IEC EN 61980, Class A	~ 18.5 dBµA/m at 10 m	-76.0 dBkW	44.3 km
25.55-25.67 MHz		~ 8.1 dBµA/m at 10 m	-52.6 dBkW	14.0 km
13.36-13.41 MHz	IEC EN 61980, Class B	-1.4 dBµA/m at 10 m	-95.9 dBkW	14.1 km
25.55-25.67 MHz		-5.8 dBµA/m at 10 m	-100.7 dBkW	6.3 km
13.36-13.41 MHz	CISPR 11 class B CIS/B/737/CDV (Table C and F) (Note 1)	-10 dBµA/m at 10 m	-104.5 dBkW	8.6 km
25.55-25.67 MHz			-104.9 dBkW	4.9 km
Note 1 : Class B CIS/B/737/CDV was rejected in CISPR				

The distance calculation is based on the EMC limits of IEC 61980-1 and ETSI EN 303 417 [4]. These limits are identical to the general EMC limits of CISPR-11 for all ISM RF devices and ERC/REC 74-01 for short range inductive devices.

The results of the studies below 30 MHz indicate the separation distance required to protect the LOFAR stations. The required separation distances to protect RAS for WPT-EV operation range from 4.9 km up to 44.3 km depending on the radiated emission.

For the sake of completeness, Figure 12 shows the results achieved based on the referenced standards. It also illustrates the relationship between the separation distance (WPT-EV and RAS) and the WPT-EV emission expressed in terms of magnetic field strength.

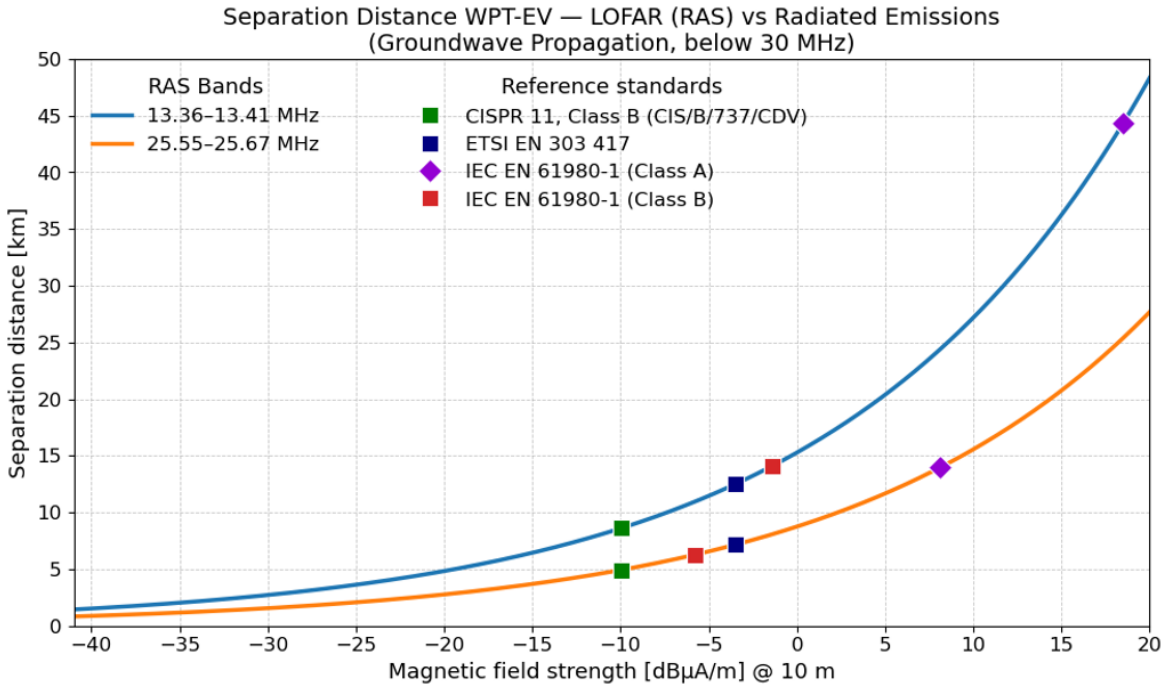


Figure 12: Separation distances between WPT-EV in operating mode and RAS (below 30 MHz) WPT spurious and harmonics emissions above 30 MHz for radio astronomy

This study assumes that the WPT-EV systems, could generate spurious emissions and harmonics extending above 30 MHz, potentially causing interference in bands allocated to RAS. Spectrum measurements presented in section 2 and Annex 8 showed that harmonics of the WPT-EV magnetic field fall below the noise level of that measurement equipment above 1 MHz. However the RAS protection criteria specified in ITU-R RA.769-2 are well below the ambient noise floor as defined in ITU-R P.372-17.

Although these bands are already shared with various services, many sensitive RAS observations are still feasible. Consequently, this study indicates that WPT-EV systems could impact frequencies also above 30 MHz.

4.5.2 Use of the bands between 30 MHz and 1 GHz by RAS

RAS uses the frequency allocations shown in the below table. Bands considered in this study are sourced from the ECA Table [2]. The analysis focuses on the frequency range up to 1 GHz, as indicated in ERC Recommendation 74-01, table 1 [5].

Table 14: RAS frequency allocation usage between 30 MHz and 1 GHz according to the ECA Table

RAS frequency bands	Type of RAS Observation
37.5-38.25 MHz	Continuum
70.45-74.8 MHz	Continuum
150.05-153 MHz	Continuum
322-328.6 MHz	Continuum, spectral line and VLBI
406.1-410 MHz	Continuum, VLBI
606-614 MHz	Continuum, VLBI

4.5.2.1 *Site-generic study*

In the following study, the propagation model outlined in Recommendation ITU-R P.452-17 [12] is valid from 100 MHz and above, therefore this study focuses exclusively on radio spectrum frequencies above 100 MHz. The performed analysis is restricted to generic site with smooth earth assumption. Furthermore, no clutter was considered as the analysis is limited to single-entry worst-case scenario. Table 15 and Table 16 show the technical parameters of WTP and RAS respectively.

The protection criteria for RAS are outlined in Recommendation ITU-R RA.769-2 [4], which are based on an integration time of 2000 seconds.

Table 15: WPT-EV technical parameters

System Parameter	Value	Remarks
Antenna height of WPT-EV, h_{WPT}	0.05 m	WPT-EV systems are typically situated underground. For simplicity, a low height is considered.
WPT spurious emission (operating mode), P_{TX}	151.525 MHz: -36 dBm	According to ETSI EN 303 417 [4]
	325.3 MHz: -36 dBm	
	408.05 MHz: -36 dBm	
	611 MHz: -54 dBm	

Table 16: Radio astronomy technical parameters

System Parameter	Value	Remarks
Integration time	2000 s	According to Recommendation ITU-R RA.769-2 [3]
Data loss	2%	According to Recommendation ITU-R RA.1513-2 [3]
Side lobe gain, G_r	0 dBi	According to Recommendation ITU-R RA.769-2, only side lobe receptions need to be considered
RAS antenna height, h_{RAS}	30 m	
Threshold interference levels	151.525 MHz: -199 dBW	According to Recommendation ITU-R RA.769-2 [3]: Table 1 for continuum observations
	325.3 MHz: -201 dBW	
	408.05 MHz: -203 dBW	
	611 MHz: -202 dBW	

According to the assumptions previously listed, the separation distances are reported in Table 17. Since almost all RAS stations observe above 30 MHz, these separation distances should be applicable to all RAS stations. The study reveals that the exclusion zones are particularly large, ranging from a few kilometres to several tens of kilometres.

Table 17: Separation distance according to spurious emission from ETSI EN 303 417 [5] for WPT-EV between 30 MHz and 1 GHz

RAS band	WPT-EV state	Spurious emission	Separation Distance according to Recommendation ITU-R P.452 [15]
150.05-153 MHz	Operating mode	250 nW (-36 dBm)	27.2 km
	Standby mode	2 nW (-57 dBm)	2.5 km
322-328.6 MHz	Operating mode	250 nW (-36 dBm)	10.6 km
	Standby mode	2 nW (-57 dBm)	0.96 km
406.1-410 MHz	Operating mode	250 nW (-36 dBm)	9.5 km
	Standby mode	2 nW (-57 dBm)	0.9 km
606-614 MHz	Operating mode	4 nW (-54 dBm)	1 km
	Standby mode	2 nW (-57 dBm)	4.1 km

4.5.2.2 *Site specific study of LOFAR Core station*

The primary RAS allocated band of 150.05-153 MHz is within the operational range of LOFAR. The impact of WPT-EV on RAS is studied, considering the terrain signal attenuation above 30 MHz. The transmitted power is assumed to be -36 dBm as specified in ETSI EN 303 417 [4]. The propagation model used is in Recommendation ITU-R P.452 [12] with a time percentage of 2% according to Recommendation ITU-R RA.1513-2 [75]. The protection criteria are based on ITU-R RA.769-2 [3], which defines a power threshold of -199 dBW (continuum observations). It is assumed a RAS antenna height of 1 m, while WPT-EV height of 0.05 m. The LOFAR core station (see Table 2) is chosen as the example site, with Lidar Terrain Data [70]. Figure 13 illustrates the calculated separation distance to protect the RAS station from WPT-EV radiated spurious emissions. The resulting separation distance is around 20 km, which is in accordance with the results of the previous generic study above 30 MHz in which 27.2 km was derived. It should be noted that, there are obstacles to the WPT-EV signal, "of which additional attenuating effect has not been modelled in this study", and therefore interference may be lower.

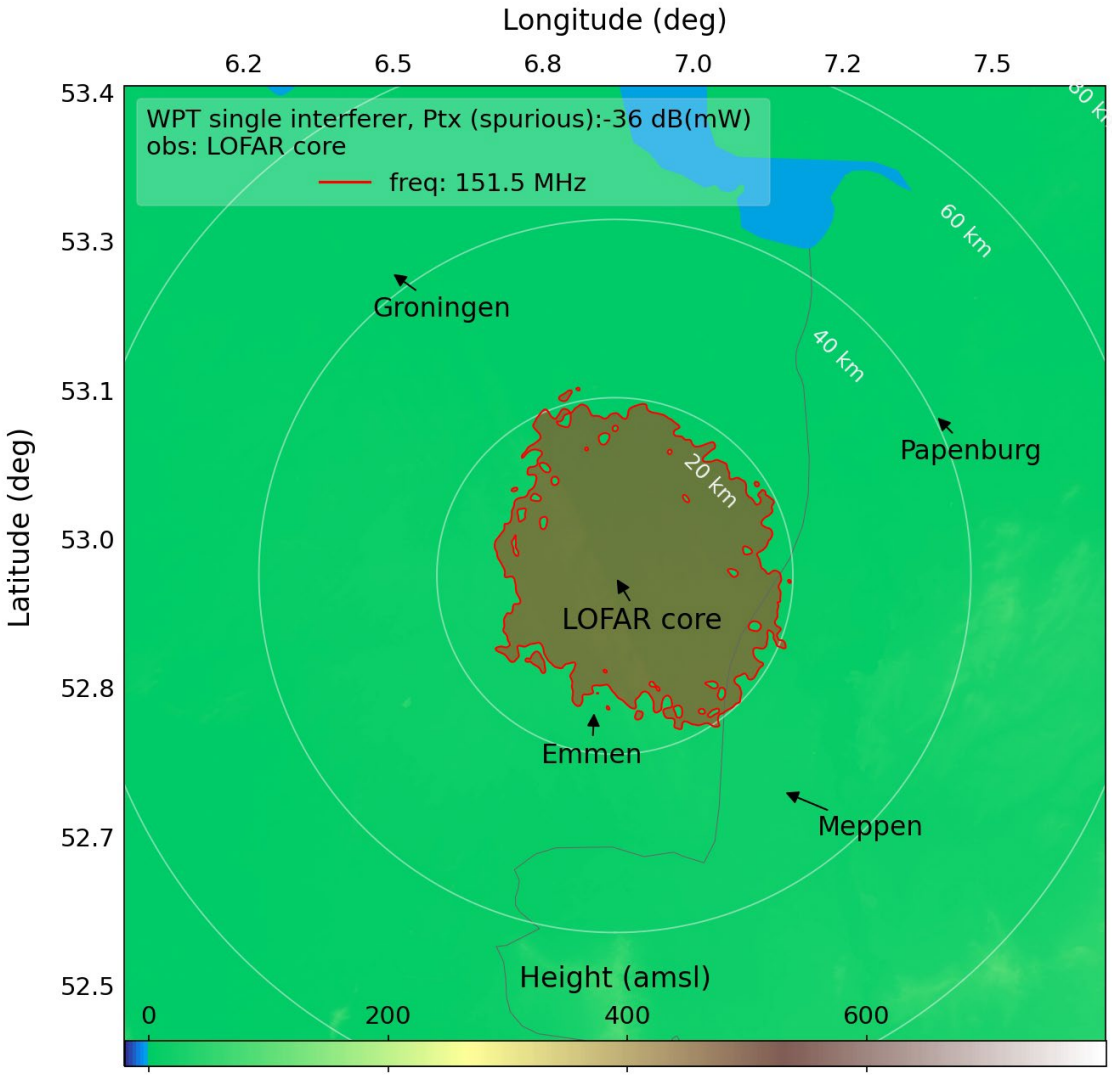


Figure 13: Separation distance from WPT-EV to LOFAR core station at 151.5 MHz

5 RESULTS OF TESTS AND MEASUREMENTS

Annex 1 and Annex 2 are studies utilizing WPT-EV systems from different companies and at different locations to test impact on the amateur service.

The study in Annex 1 occurred in the United States (Cedar Park, Texas) and specifically studied the amateur bands including the following: 80 m band (3.5 MHz to 4 MHz), 30 m band (10.10 MHz to 10.15 MHz), and 20 m band (14 MHz to 14.35 MHz). ANNEX 1: consisted of standardised EMC measurements based on CISPR 16-2-3 [64] and CISPR 11 [6] on an Open Area Test Site (OATS) and qualitative audio impact assessment utilizing a typical amateur receiver in the amateur bands. The WPT-EV system utilised in Annex 1 was a SAE J2954 [21] prototype system that did not meet all unwanted limit requirements indicated in Recommendation ITU-R SM.329-12 [13] nor did it meet all unwanted limit requirements indicated in CISPR 11, edition 6.2 [6]. Annex 1 concluded that, in the environmental conditions at the test site, the system did not produce any qualitative impact in most cases to an amateur radio station located 10 m from the WPT-EV operation at 11.1 kW; however, in one specific condition an "amateur service signal operating in the far-field with an estimated average E-Field strength of ~16 dBµV/m (-35 dBµA/m) was heard at a frequency coinciding with a WPT harmonic and resulted in an intelligible and audible voice transmission yielding non-harmful interference. In this case, the approximate amateur signal-to-ambient-noise-peak ratio was about 13 dB with the ambient noise peaks occurring at an estimated average of ~-2 dBµV/m (-53.5 dBµA/m). (It should be noted that the amateur signal level values are estimated based on uncalibrated Software Defined Radio (SDR) measurements and thus have a margin of error in the estimation.)"

The study in Annex 2 occurred in Ersigen, Switzerland (Ersigen)utilizing series-production WPT-EV system f. The studies in Annex 2 consisted of standardised EMC measurements based on CISPR 16-2-3 [64] and CISPR 11 [6] and qualitative amateur radio assessment. The study concluded that, "No interferences could be observed during this trial between the WPT system and amateur radio communication in a residential environment with moderate man-made disturbances. Measurements using the magnetic loop antenna showed a peak at the WPT operating frequency, which was clearly discernible from the background emission. It should be noted, that disturbances measured by the amateur antenna are significantly lower than disturbances measured by the loop antenna, which may be due the directivity of the antenna used by the amateur station. The emissions generated by the WPT system at frequencies above 150 kHz were comparable to the observed background emission (either background noise or measuring equipment noise) so that no clear distinction between the two, i.e. WPT system on or off, could be made."

The study in Annex 3 provides an assessment of median signals in the amateur service in one rural location in England utilizing receiver drawn from off-air measurements. Annex 3 compares these median signal levels to limits defined in ERC Recommendation 74-01 [5] for inductive SRDs. Annex 3 concludes that the studies in Annex 1 and Annex 2 might have been performed in higher noise environments than the study in Annex 3 and shows that potential harmonic emissions from WPT-EV if they were to be at ERC Recommendation 74-01 levels (broadly the same as CISPR 11) would exceed the mean level of off-air amateur service signals typically measured in a rural environment by some 10-30 dB or more, when using a loop antenna. When using a vertical monopole, the fall-off in gain at low elevations may help reduce the impact of nearby WPT emissions at such angles. The impact using a dipole antenna was not studied. Annex 3 concludes with the following:

" a) The measured level of signals in one rural location in the amateur service bands indicated have S/N ratios of some 10-30 dB at the receiver with a median of some 20 dB. Median signal levels were typically -45 dBuA/m.

b) According to measurements from an SDR at one location, emissions at the limits of ERC Recommendation 74-01 at a measurement distance of 10 m could exceed the levels of amateur service signals by 10-30 dB or more when using a magnetic loop antenna.

When using a vertical monopole E-Field antenna, the comparative levels cannot be stated for sure. For 7, 10, and 14 MHz at least, the 10 m spacing places the antenna in the far field and so emissions are likely to be close to the H-field levels converted using free-space impedance but will be attenuated by the reduced gain of the monopole including the effects of low elevation angles."

6 AGGREGATE STUDIES ON WPT-EV

6.1 METHODOLOGY

6.1.1 Electromagnetic field Equations

Unwanted emission level of WPT-EV is often characterised by a magnetic field level which should not be exceeded. Modelling the radiated field with a small loop antenna model (though this model is a simplification of reality), the electric field and magnetic field vectors can be expressed by:

$$E_r = E_\theta = 0$$

$$E_\varphi = -\frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{jk}{r} + \frac{1}{r^2}\right)\sin(\theta)$$

$$H_r = \frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{2}{\eta r^2} + \frac{2}{j\omega\mu r^3}\right)\cos(\theta)$$

$$H_\theta = \frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{j\omega\varepsilon}{r} + \frac{1}{\eta r^2} + \frac{1}{j\omega\mu r^3}\right)\sin(\theta)$$

$$H_\varphi = 0$$

$$k = \omega\sqrt{\mu\varepsilon}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

$\mu = 4\pi \times 10^{-7} H/m$ is the magnetic constant, $\varepsilon = 8{,}854\,187 \times 10^{-12}\, F/m$ is the air permittivity. M is the magnetic moment of the electromagnetic field. Its value is computed so that the amplitude of the magnetic field is at the studied limit (see example of IEC 61980 [7], represented below).

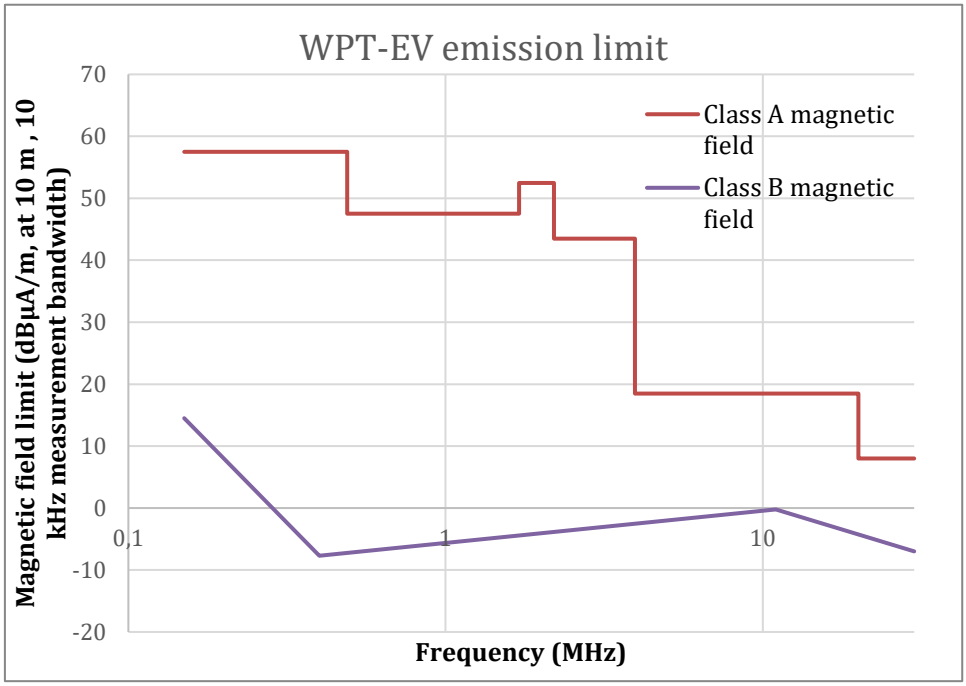


Figure 14: Example from IEC 61980 [8] of WPT-EV emission limit

The orientation of electric and magnetic fields, as well as the spherical and cartesian coordinate systems are represented in Figure 15.

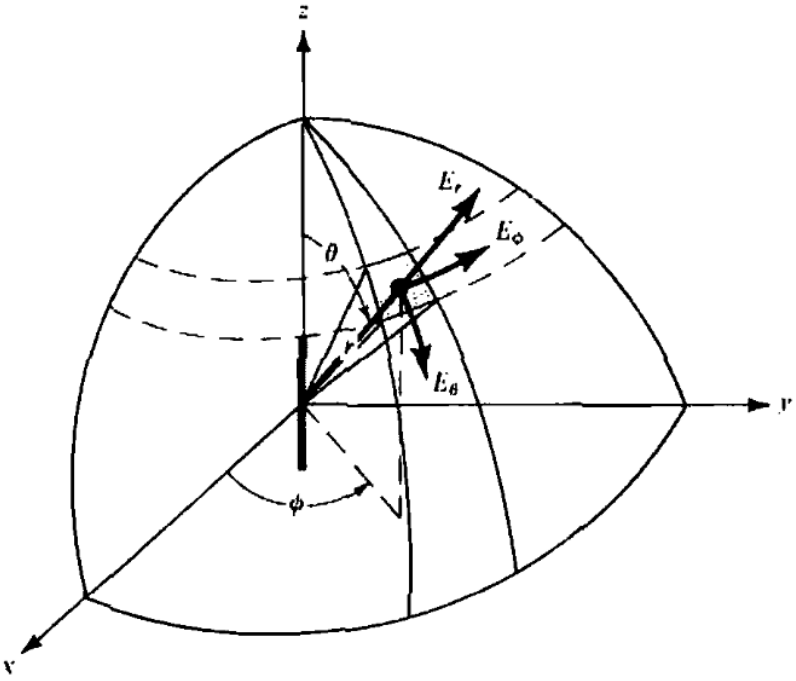


Figure 15: Spherical and cartesian coordinate systems and orientation of electric field vector

The transition matrix from the spherical coordinate system to cartesian coordinate system is:

$$T = \begin{pmatrix} \sin(\theta)\cos(\varphi) & \cos(\theta)\cos(\varphi) & -\sin(\varphi) \\ \sin(\theta)\sin(\varphi) & \cos(\theta)\sin(\varphi) & \cos(\varphi) \\ \cos(\theta) & -\sin(\theta) & 0 \end{pmatrix}$$

As a consequence, in the cartesian coordinate system, the electric and magnetic fields at the affected receiver level can be expressed by:

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = T \begin{pmatrix} E_r \\ E_\theta \\ E_\varphi \end{pmatrix} = \begin{pmatrix} -\sin(\varphi)\, E_\varphi \\ \cos(\varphi)\, E_\varphi \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix} = T \begin{pmatrix} H_r \\ H_\theta \\ H_\varphi \end{pmatrix} = \begin{pmatrix} \sin(\theta)\cos(\varphi)\, H_r + \cos(\theta)\cos(\varphi)\, H_\theta \\ \sin(\theta)\sin(\varphi)\, H_r + \cos(\theta)\sin(\varphi)\, H_\theta \\ \cos(\theta)\, H_r - \sin(\theta)\, H_\theta \end{pmatrix}$$

In the above equation, the coordinate (r, θ, φ) can be expressed as a function of the cartesian coordinates of the victim receiver and WPT-EV, respectively denoted (x_{Rx}, y_{Rx}, z_{Rx}) and $(x_{WPT}, y_{WPT}, z_{WPT})$.

$$r = \sqrt{(x_{Rx} - x_{WPT})^2 + (y_{Rx} - y_{WPT})^2 + (z_{Rx} - z_{WPT})^2}$$

$$\theta = \operatorname{acos}\left(\frac{z_{Rx} - z_{WPT}}{\sqrt{(x_{Rx} - x_{WPT})^2 + (y_{Rx} - y_{WPT})^2 + (z_{Rx} - z_{WPT})^2}}\right)$$

$$\varphi = \operatorname{atan}\left(\frac{y_{Rx} - y_{WPT}}{x_{Rx} - x_{WPT}}\right)$$

6.2 APPLICATION TO AGGREGATE SCENARIO

N WPT-EV with cartesian coordinates $\left(x_{WPT,i}, y_{WPT,i}, z_{WPT,i}\right)_{i\in[\![1;N]\!]}$ are considered.

The aggregate electric and magnetic field at the victim receiver position (cartesian coordinates (x_{Rx}, y_{Rx}, z_{Rx})) can be expressed by:

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \sum_{i=1}^{N} \alpha_i \begin{pmatrix} -\sin(\varphi_i)\, E_{\varphi,i} \\ \cos(\varphi_i)\, E_{\varphi,i} \\ 0 \end{pmatrix} vis(\theta_i) e^{j\delta_i(t)}$$

$$\begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix} = \sum_{i=1}^{N} \alpha_i \begin{pmatrix} \sin(\theta_i)\cos(\varphi_i)\, H_{r,i} + \cos(\theta_i)\cos(\varphi_i)\, H_{\theta,i} \\ \sin(\theta_i)\sin(\varphi_i)\, H_{r,i} + \cos(\theta_i)\sin(\varphi_i)\, H_{\theta,i} \\ \cos(\theta_i)\, H_{r,i} - \sin(\theta_i)\, H_{\theta,i} \end{pmatrix} vis(\theta_i) e^{j\delta_i(t)}$$

With:

$$r_i = \sqrt{\left(x_{Rx} - x_{WPT,i}\right)^2 + \left(y_{Rx} - y_{WPT,i}\right)^2 + \left(z_{Rx} - z_{WPT,i}\right)^2}$$

$$\theta_i = \operatorname{acos}\left(\frac{z_{Rx} - z_{WPT,i}}{\sqrt{\left(x_{Rx} - x_{WPT,i}\right)^2 + \left(y_{Rx} - y_{WPT,i}\right)^2 + \left(z_{Rx} - z_{WPT,i}\right)^2}} \right)$$

$$\varphi_i = \operatorname{atan}\left(\frac{y_{Rx} - y_{WPT,i}}{x_{Rx} - x_{WPT,i}} \right)$$

$$E_{\varphi,i} = -\frac{j\omega\mu M}{4\pi}\, e^{jkr_i} \left(\frac{jk}{r_i} + \frac{1}{r_i^2} \right) \sin(\theta_i)$$

$$H_{r,i} = \frac{j\omega\mu M}{4\pi}\, e^{jkr_i} \left(\frac{2}{\eta r_i^2} + \frac{2}{j\omega\mu r_i^3} \right) \cos(\theta_i)$$

$$H_{\theta,i} = \frac{j\omega\mu M}{4\pi} e^{jkr_i} \left(\frac{j\omega\varepsilon}{r_i} + \frac{1}{\eta r_i^2} + \frac{1}{j\omega\mu r_i^3} \right) \sin(\theta_i)$$

α_i is the random parameter characterising the probability that the WPT-EV i radiate at a given time. It is suggested to model it as a Bernouilli distribution with probability equal to the activity factor.

$\delta_i(t)$ is the instantaneous phase of the WPT-EV. It is assumed that $\delta_i(t)$ has a uniform distribution over $[0; 2\pi]$.

$vis(\theta_i)$ is a factor accounting for the shielding provided by the vehicle above the WPT-EV:

$$|vis(\theta_i)|^2 = \begin{cases} 0\ dB\ for\ 0° \le \theta_i \le 45° \\ 15\ dB\ for\ 45° \le \theta_i \le 90° \end{cases}$$

Consideration of polarisation

It can be denoted that $\vec{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$ the normalised polarisation vector of the antenna affected by the WPT-EV. The amplitude of the received electrical field could then be expressed as:

$$|E_{Rx}|^2 = \left|\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}.\vec{p}\right|^2 = \left|\sum_{i=1}^{N} \alpha_i vis(\theta_i)\left(-\sin(\varphi_i)\, E_{\varphi,i} p_x + \cos(\varphi_i)\, E_{\varphi,i} p_y\right) e^{j\delta_i(t)}\right|^2$$

$$= \sum_{i=1}^{N} \alpha_i |vis(\theta_i)|^2 \left|-\sin(\varphi_i)\, E_{\varphi,i} p_x + \cos(\varphi_i)\, E_{\varphi,i} p_y\right|^2$$

$$+ 2\sum_{i=1}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{N} Re\{\alpha_i vis(\theta_i)\alpha_j vis(\theta_j)\left(-\sin(\varphi_i)\, E_{\varphi,i} p_x + \cos(\varphi_i)\, E_{\varphi,i} p_y\right)\left(-\sin(\varphi_j)\, E_{\varphi,j} p_x\right.$$

$$\left. + \cos(\varphi_j)\, E_{\varphi,j} p_y\right) e^{j\delta_i(t)} e^{j\delta_j(t)}\}$$

Assuming unsynchronised WPT-EV stations, the average value in time of the second term would be equal to 0 as $\theta_i(t)$ and $\theta_j(t)$ would be uncorrelated.

With this assumption, the above equation can be simplified as follows:

$$\mathbb{E}(|E_{Rx}|^2) = \sum_{i=1}^{N} \mathbb{E}(\alpha_i)|vis(\theta_i)|^2 \left|-\sin(\varphi_i)\, E_{\varphi,i} p_x + \cos(\varphi_i)\, E_{\varphi,i} p_y\right|^2$$

$$= \sum_{i=1}^{N} AF\ |vis(\theta_i)|^2 \left|-\sin(\varphi_i)\, E_{\varphi,i} p_x + \cos(\varphi_i)\, E_{\varphi,i} p_y\right|^2$$

AF is the activity factor.

Similarly, the received magnetic field can be expressed as:

$$\mathbb{E}(|H_{Rx}|^2) = \sum_{i=1}^{N} AF\ |vis(\theta_i)|^2 \left|\begin{matrix} \left(\sin(\theta_i)\cos(\varphi_i)\, H_{r,i} + \cos(\theta_i)\cos(\varphi_i)\, H_{\theta,i}\right) p_x \\ +\left(\sin(\theta_i)\sin(\varphi_i)\, H_{r,i} + \cos(\theta_i)\sin(\varphi_i)\, H_{\theta,i}\right) p_y \\ +\left(\cos(\theta_i)\, H_{r,i} - \sin(\theta_i)\, H_{\theta,i}\right) p_z \end{matrix}\right|^2$$

It is proposed to perform the calculation with:

- Maximum polarisation of electrical field: the receiver antenna polarisation which maximises the received electrical field

$$\mathbb{E}(|E_{Rx}|^2) = AF \sum_{i=1}^{N} |vis(\theta_i)|^2 \left(\left|-\sin(\varphi_i)\, E_{\varphi,i}\right|^2 + \left|\cos(\varphi_i)\, E_{\varphi,i}\right|^2\right)$$

- Maximum polarisation of magnetic field: the receiver antenna polarisation which maximises the received magnetic field

$$\mathbb{E}(|H_{Rx}|^2) = AF \sum_{i=1}^{N} |vis(\theta_i)|^2 \left(\begin{matrix} \left|\left(\sin(\theta_i)\cos(\varphi_i)\, H_{r,i} + \cos(\theta_i)\cos(\varphi_i)\, H_{\theta,i}\right)\right|^2 \\ +\left|\left(\sin(\theta_i)\sin(\varphi_i)\, H_{r,i} + \cos(\theta_i)\sin(\varphi_i)\, H_{\theta,i}\right)\right|^2 \\ +\left|\left(\cos(\theta_i)\, H_{r,i} - \sin(\theta_i)\, H_{\theta,i}\right)\right|^2 \end{matrix}\right)$$

- Horizontal polarisation: $\vec{p} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

$$\mathbb{E}(|E_{Rx}|^2) = AF \sum_{i=1}^{N} |vis(\theta_i)|^2 \sin^2(\varphi_i) \left|E_{\varphi,i}\right|^2$$

$$\mathbb{E}(|H_{Rx}|^2) = AF \sum_{i=1}^{N} |vis(\theta_i)|^2 \left|\sin(\theta_i)\cos(\varphi_i)\, H_{r,i} + \cos(\theta_i)\cos(\varphi_i) H_{\theta,i}\right|^2$$

- Vertical polarisation: $\vec{p} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

$$\mathbb{E}(|H_{Rx}|^2) = AF \sum_{i=1}^{N} |vis(\theta_i)|^2 \left|\cos(\theta_i)\, H_{r,i} - \sin(\theta_i)\, H_{\theta,i}\right|^2$$

It is also proposed to study several assumptions on activity factor: 20%, 50%, 100%.

6.3 SCENARIOS

6.3.1 Cluster

A cluster of 16 WPT-EV localised on the same site, separated by 6 m from each other, is assumed, as an example to examine the impact of WPT-EV if deployed in a commercial parking area.



Figure 16: Deployment of a cluster of 16 WPT-EV

6.3.2 Spread WPT-EV

A density of 64 WPT-EV per km², which corresponds to 125 m separation distance between WPT-EVs, whose deployment is represented in the below figure, is assumed.

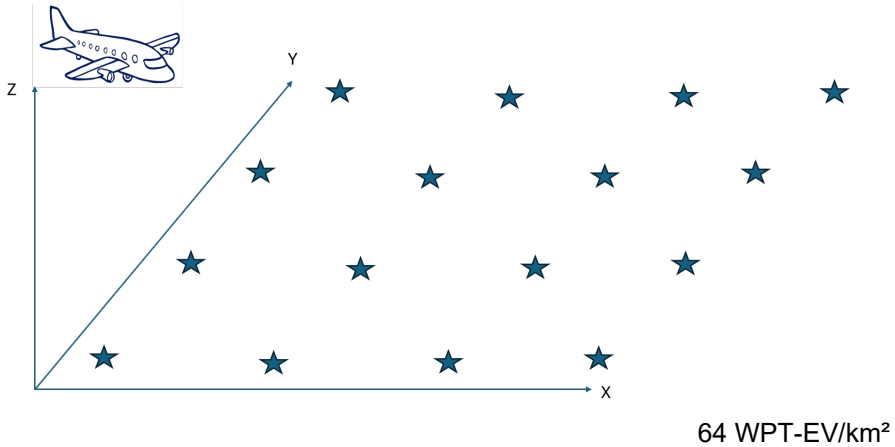


Figure 17: Deployment of spread WPT-EV

6.4 RESULTS

This section provides the examples of aggregation results. The parameters for aggregation study scenarios are given in Table 18.

Table 18: Parameters for aggregation study scenarios

	Scenario 1 NDB receiver onboard aircraft	Scenario 2 HF ground station	Scenario 3 HF airborne station
Frequency (Note 1)	535 kHz	11.3 MHz	11.3 MHz
Victim receiver antenna height	250 ft	10 m	4500 ft
Magnetic field strength level used in the calculations (dBµA/m)	-64.7 dBµA/m	-70.1 dBµA/m	
Electric field strength level used in the calculations (dBµV/m)	-13.2 dBµV/m	-18.6 dBµV/m	
Note 1: These frequencies are selected for which the link budget is minimum.			

6.4.1 Cluster scenario

6.4.1.1 *Scenario 1*

The below figure represents the margin for scenario 1. The margin is computed by subtracting the protection threshold given in Table 1 to the magnetic and electric fields computed in section 2. No activity factor is included. The left-hand figure provides the result for a single WPT-EV positioned at (0;0) and the right-hand figure provides the aggregation results for the cluster defined in section 6.3 centred around (0;0).

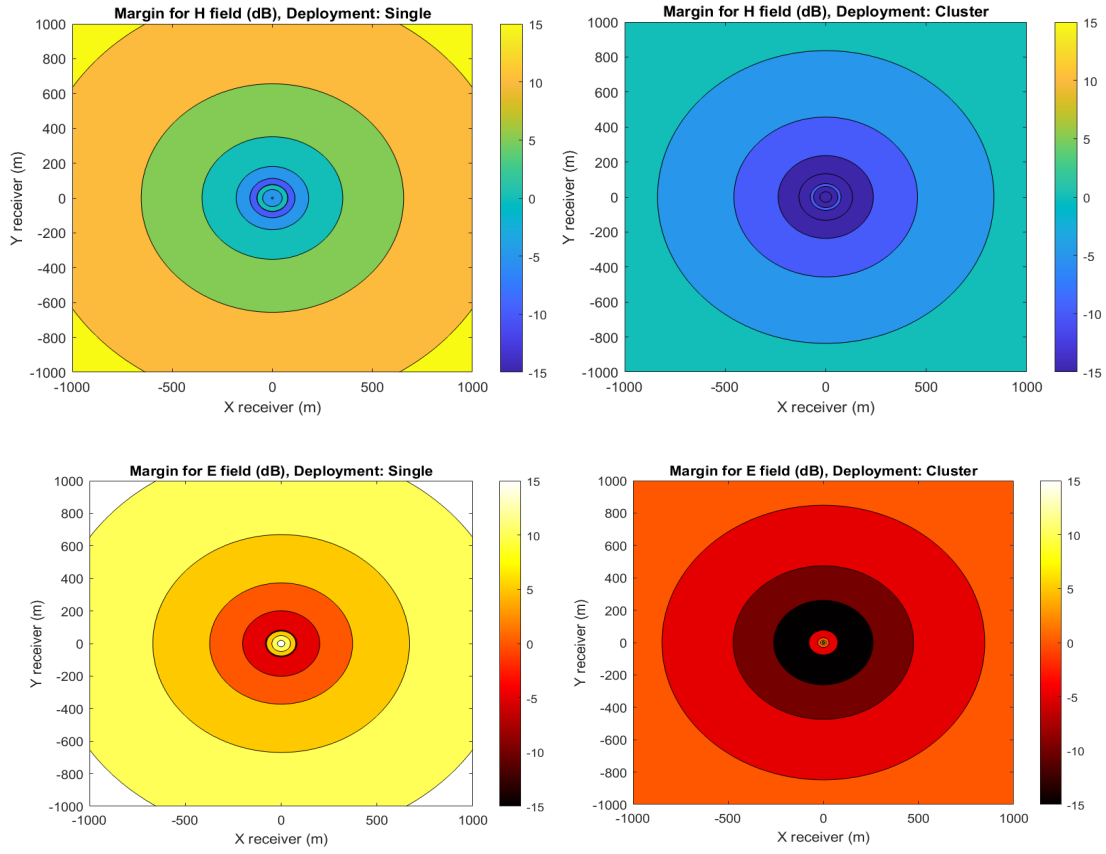


Figure 18: Case 1: No polarisation losses accounted

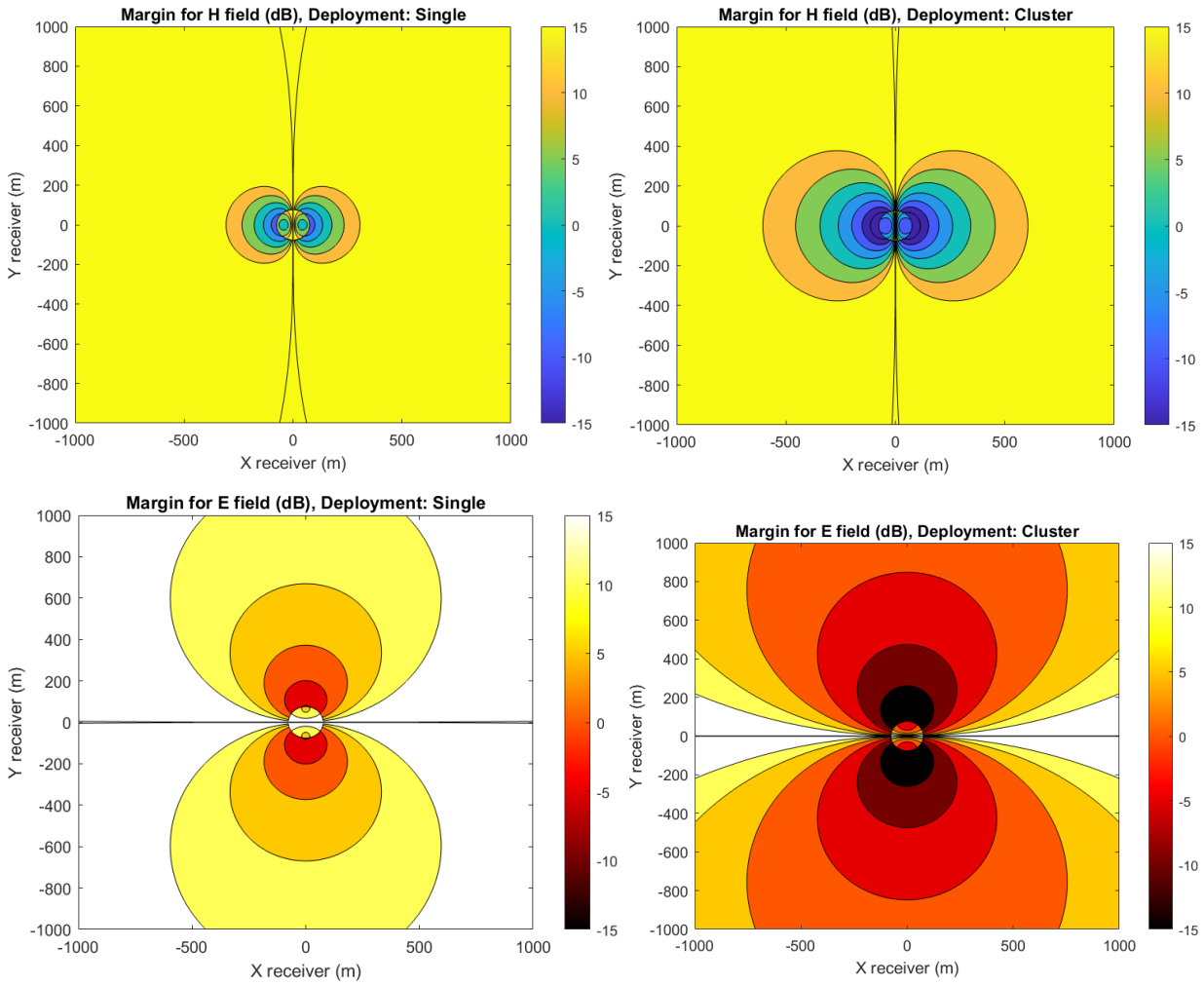


Figure 19: Case 2: Linear polarisation

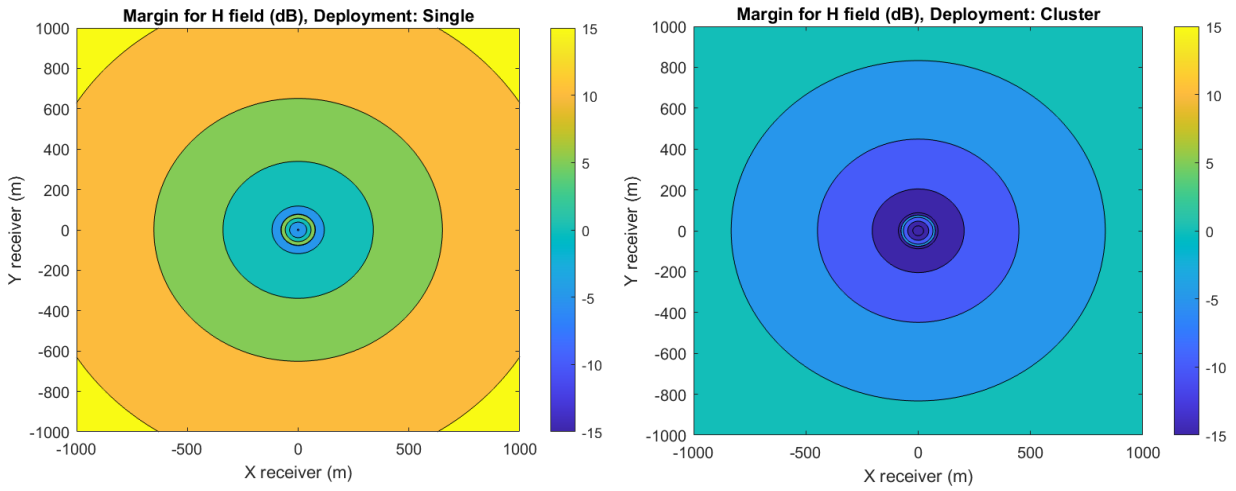


Figure 20: Case 3: Vertical polarisation

For scenario 1 and considering the different assumptions on the polarisation, it should be noted that the aggregate case includes an increase of around 12 dB in the received field, in a region sufficiently far from the

cluster. This corresponds to 10log(N), where N=16 is the number of WPT-EV devices in the cluster. Assuming statistical independence on the use of the WPT-EV chargers in the simulation, the inclusion of the activity factor is the calculation would improve the margin with a factor 10log(AF) (i.e. 7 dB for a 20% activity factor or 3 dB for a 50% activity factor).

6.4.1.2 Scenario 2

The figures below represent the margin for scenario 2. The margin is computed by subtracting the protection threshold given in Table 1 to the magnetic and electric fields computed in section 2. No activity factor is included. The left-hand figure provides the result for a single WPT-EV positioned at (0;0) and the right-hand figure provides the aggregation results for the cluster defined in section 6.3 centred around (0;0).

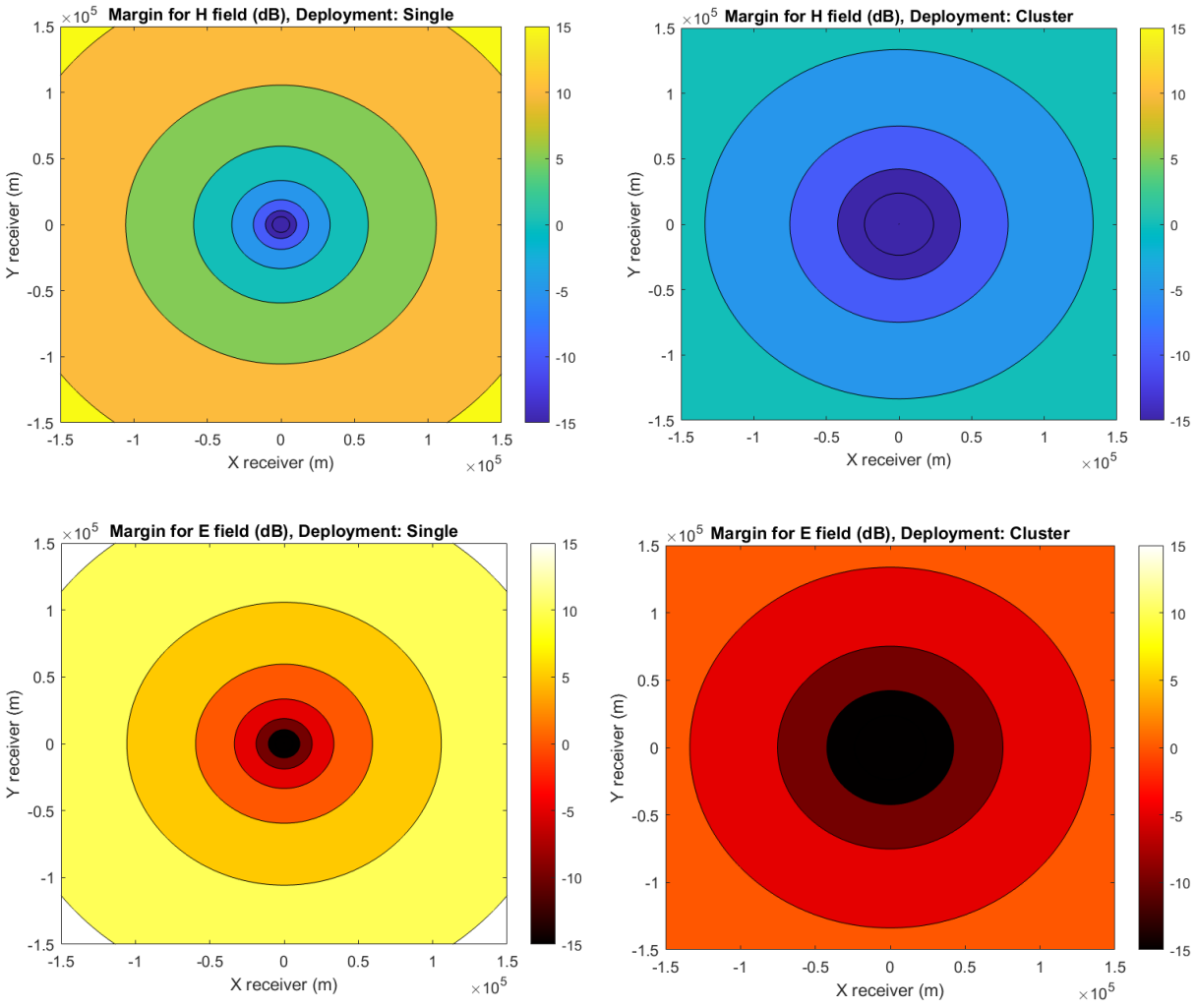


Figure 21: Case 1: No polarisation losses accounted

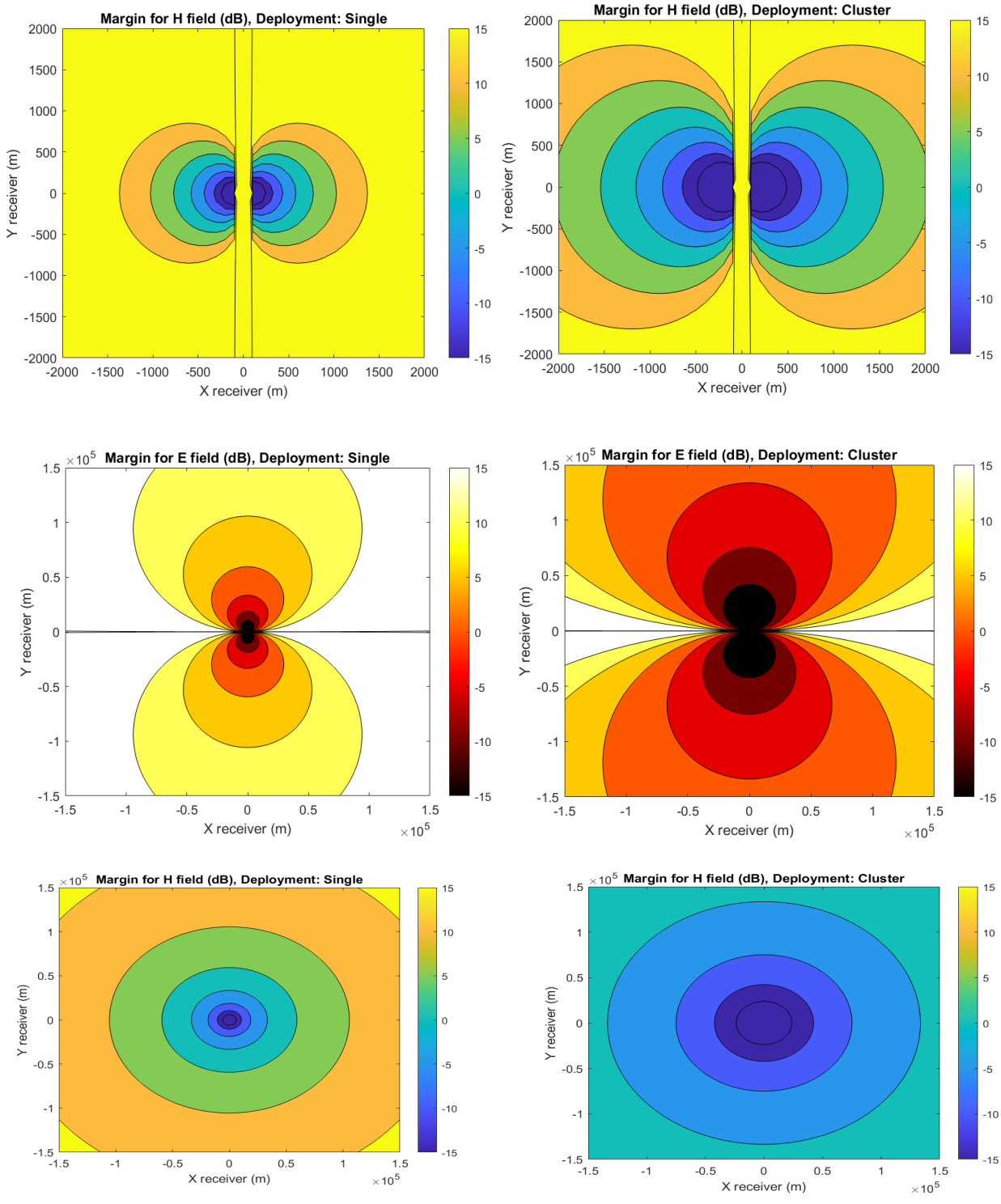


Figure 22: Case 3: Vertical polarisation

For this scenario 2 and considering the different assumptions on the polarisation, it should be noted that the aggregate case includes an increase of around 12 dB in the received field, in a region sufficiently far from the cluster. This corresponds to 10log(N), with N=16 is the number of WPT-EV devices in the cluster. Assuming statistical independence on the use of the WPT-EV chargers in the simulation, the inclusion of the activity factor is the calculation would improve the margin with a factor 10log(AF) (i.e. 7 B for a 20% activity factor or 3 dB for a 50% activity factor).

6.4.2 Spread WPT-EV scenario

For spread WPT-EV configuration, only scenario 3 is investigated. Note that the spread WPT-EV configuration is not relevant for ground receiver or receiver at low altitude, because the visible areas (and consequently the number of WPT-EV) would be limited for such receivers. In this section, WPT-EV are located as described in section over an area of 30*30 km. The density of WPT-EV is 64 per km-2.

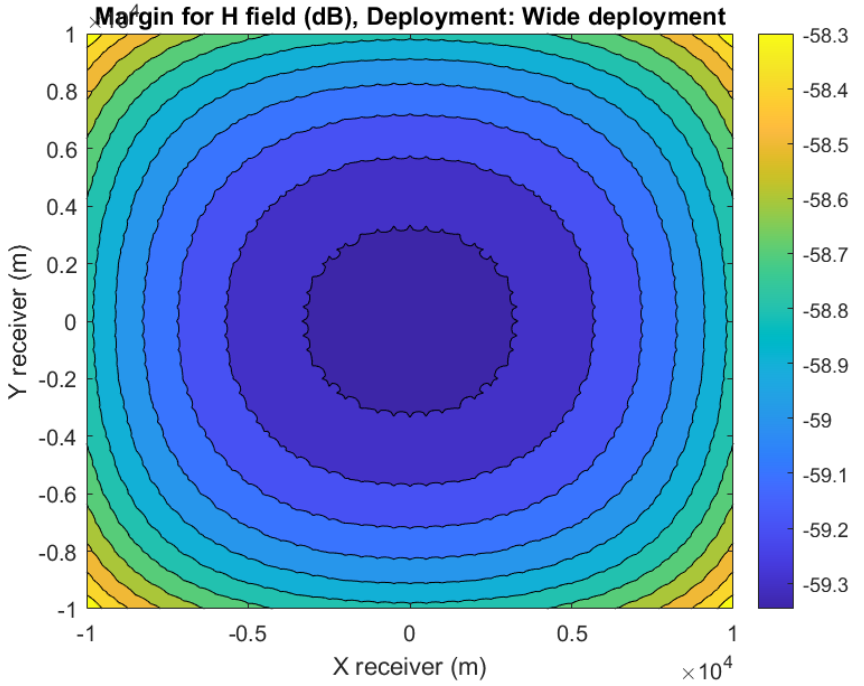


Figure 23: Case 1: No polarisation losses accounted

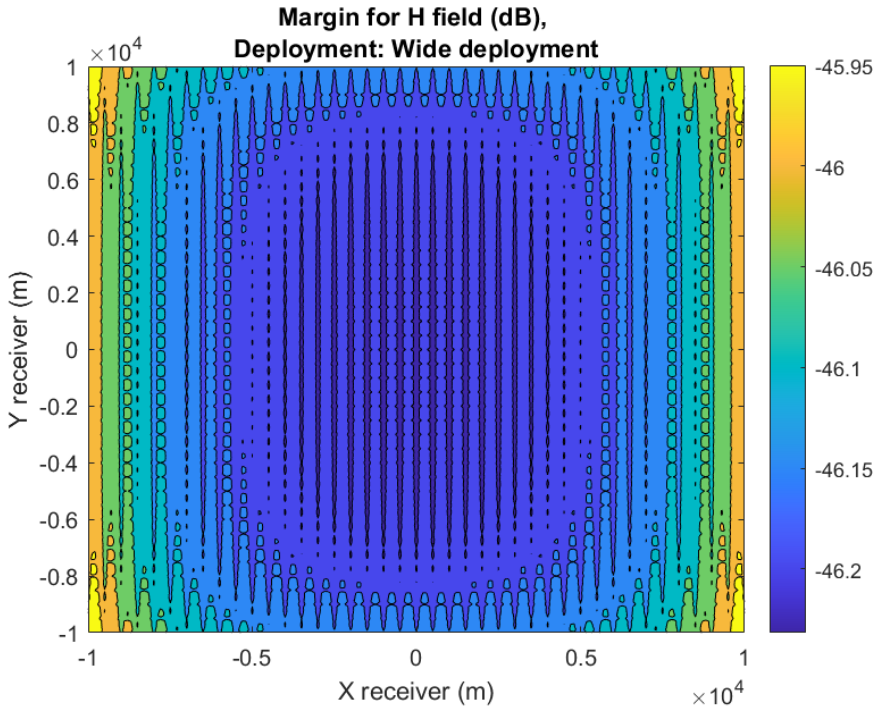


Figure 24: Case 2: Linear polarisation

ANNEX 1: STUDIES CONDUCTED IN THE USA ON IMPACT OF WPT-EV ON AMATEUR RADIO

A1.1 ABSTRACT

This impact study reviews the current status of amateur radio regulations and selected allocated HF bands in the United States as of February 2020. A standard pre-production prototype ~11 kW WPT-EV system mounted on a consumer vehicle is described. Radiated emissions testing was performed with the WPT-EV system in accordance with standardised international practices including CISPR 16-2-3 [64], CISPR 11 [6], the IEC 61980 series [7] and ANSI C63.30 [66] at an accredited third-party open area test site and the results compared with typical amateur radio equipment used. Calibrated data was collected by the third-party lab and licensed amateur radio operators performed the amateur radio tests to collect data both with a calibrated spectrum analyser and off-the-shelf amateur radio equipment. The study attempts to identify interference potential caused by the harmonics of standardised WPT-EV systems in a real-world environment. Additional detailed characteristic data of the WPT-EV system is also.

A1.2 INTRODUCTION

12 Amateur operators use many different types of analogue and digital communication techniques such as SSB AM (single side-band amplitude modulation), CW (continuous wave), FM (frequency modulation), TV, PACTOR, PSK31, RTTY and other modes.

Some amateur operators create homemade transceivers; however, most amateur transceivers are purchased from commercial sources known for their amateur radio equipment. A review of mobile and base station transceiver products from popular sources indicate all the HF products (including most portable transceivers) can transmit using a number of analogue and digital operating modes on bands starting with the 80 m band (3.5 MHz to 4 MHz) and going up in frequency to the 6 m (50 MHz to 54 MHz) or 2 m (144 MHz to 148 MHz) bands. Most base station transceivers also have the capability to go as low in frequency as the 160 m band (1.8 MHz to 2 MHz). The longer wavelengths of the low frequency bands also require much larger antennas for effective radio communication meaning that most portable HF antennas target the 80 m to 6 m bands for operation which isn't fixed to a station location. Most commercial transceivers can transmit at power levels from 50 W to 200 W and require a separate linear power amplifier to operate at higher power levels. FCC's Title 47, Part § 97.313 requires the use of minimum necessary power to carry out the desired communications, but it allows operators to transmit up to 1.5 kW peak envelope power (PEP) for the 80 m, 40 m and 20 m HF bands; and up to 200 W PEP for the 30 m HF band.

Ionospheric propagation is one of the key modes of propagation used in the HF bands enabling communication over distances of thousands of kilometres in some cases. Amateur operators utilizing the HF bands make extensive use of these "skywave" propagation modes to communicate with other licensed amateur operators in all continents around the globe. The lower frequency bands such as the 80 m and 40 m band are favoured for communication within shorter ranges (e.g. <1000 km) or even shorter (e.g. <100 km) using Near Vertical Incidence Skywave (NVIS) modes.

For the qualitative assessment of impact that is part of this impact study, the 80 m and 40 m amateur radio bands were determined to be the most feasible and likely to be impacted from harmonics originating from a WPT-EV system operating in the frequency range of 79-90 kHz (~ 85 kHz nominal). Additional data was also collected for the 30 m (10.10 MHz to 10.15 MHz) and 20 m (14 MHz to 14.35 MHz) bands as well. For practical reasons, the 160 m band was not tested, although the amateur operators doing the testing agreed that data from the 80 m band could reasonably be extrapolated to the 160 m band. The impact study was executed by a SAE J2954 [21] Cooperative Research Program made up of many automakers and several suppliers. All testing was performed by an independent EMC lab at TDK RF Solutions in Cedar Park [18], Texas using an accredited Open Area Test Site (OATS). One or more licensed amateur radio operators, all of whom were also members or staff of ARRL, or officials within the International Amateur Radio Union were also involved in collecting the qualitative assessment data and selecting the appropriate amateur equipment.

A1.3 CHARACTERISTICS OF STANDARDISED WPT-EV SYSTEMS

For the purposes of this impact study, only WPT-EV systems designed to meet the SAE J2954 [21] and related WPT-EV standards, with specific characteristics outlined in section 2, were considered.

A1.4 MEASUREMENTS PERFORMED ON AN OPEN AREA TEST SITE (OATS)

A1.4.1 Characteristics of the WPT-EV Equipment Under Test (EUT)

The WPT-EV system used for this impact study was a prototype pre-production system with the vehicle coil assembly mounted on a Nissan Leaf just behind its front axle at a height providing a ground clearance of 175 mm. The WPT-EV system comprised of a wall box power supply, the ground assembly and the vehicle assembly together with the vehicle corresponding to a typical garage setting is considered the EUT. The vehicle assembly was operationally connected for charging the vehicle's traction battery. The power input level to the WPT-EV was ~11.1 kW complying with the WPT3 power class as defined by SAE J2954 [21]. For radiated emissions testing, in order to reduce undesirable effects of the ground plane, the vehicle and the ground assembly were raised 15 cm from the OATS metal floor as recommended by several standards bodies (to better emulate real-world conditions and avoid parasitic metal ground plane interaction). The coil of the vehicle assembly was centered on the turn table and worst-case alignment offsets were set by shifting the ground assembly coil accordingly. Standard EMC practices based on international standards for radiated emissions testing were applied.



Figure 25: WPT-EV System Setup for Radiated Emissions Testing on an OATS (Side View)



Figure 26: WPT-EV System Setup for Radiated Emissions Testing on an OATS (Front View)

The design of the particular WPT-EV study used is based on the criteria and details outlined in SAE J2954 [21], ISO 19363 [62] and IEC 61980 [7]. The system operates at a fixed frequency of 85 kHz and utilizes magnetic resonance to transfer its energy at that frequency. While the magnetic field emanating directly from ground assembly coil is not the only possible source of emissions, it is generally the source of most discussion regarding potential impact of WPT-EV on radio broadcasts and amateur radio reception.

A1.4.2 Characteristics of the OATS

The OATS used for testing is owned by TDK RF Solutions, Incorporated and is located in Cedar Park, Texas near Austin, Texas. All measurements were made at this A2LA accredited calibration lab. A satellite image of the OATS can be seen below.

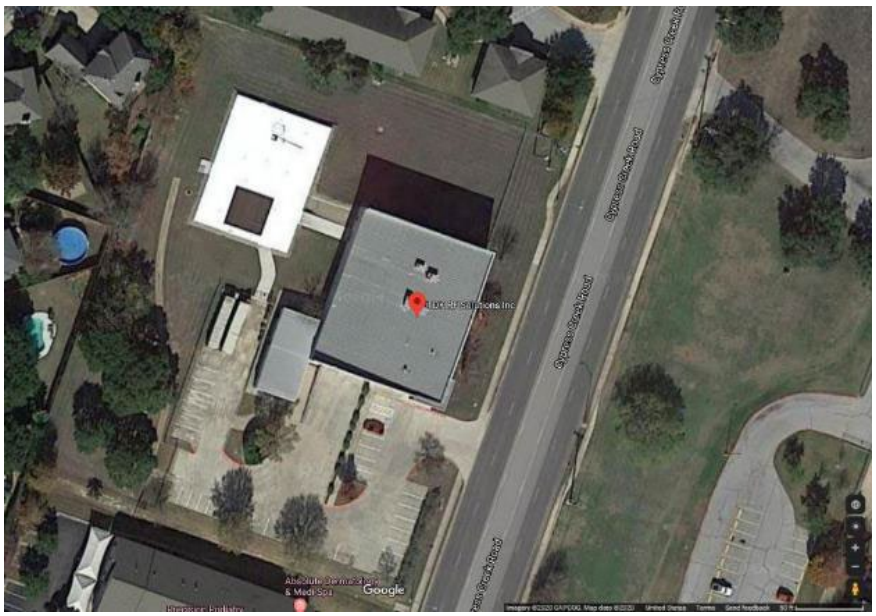


Figure 27: Satellite image of TDK RF Solutions OATS

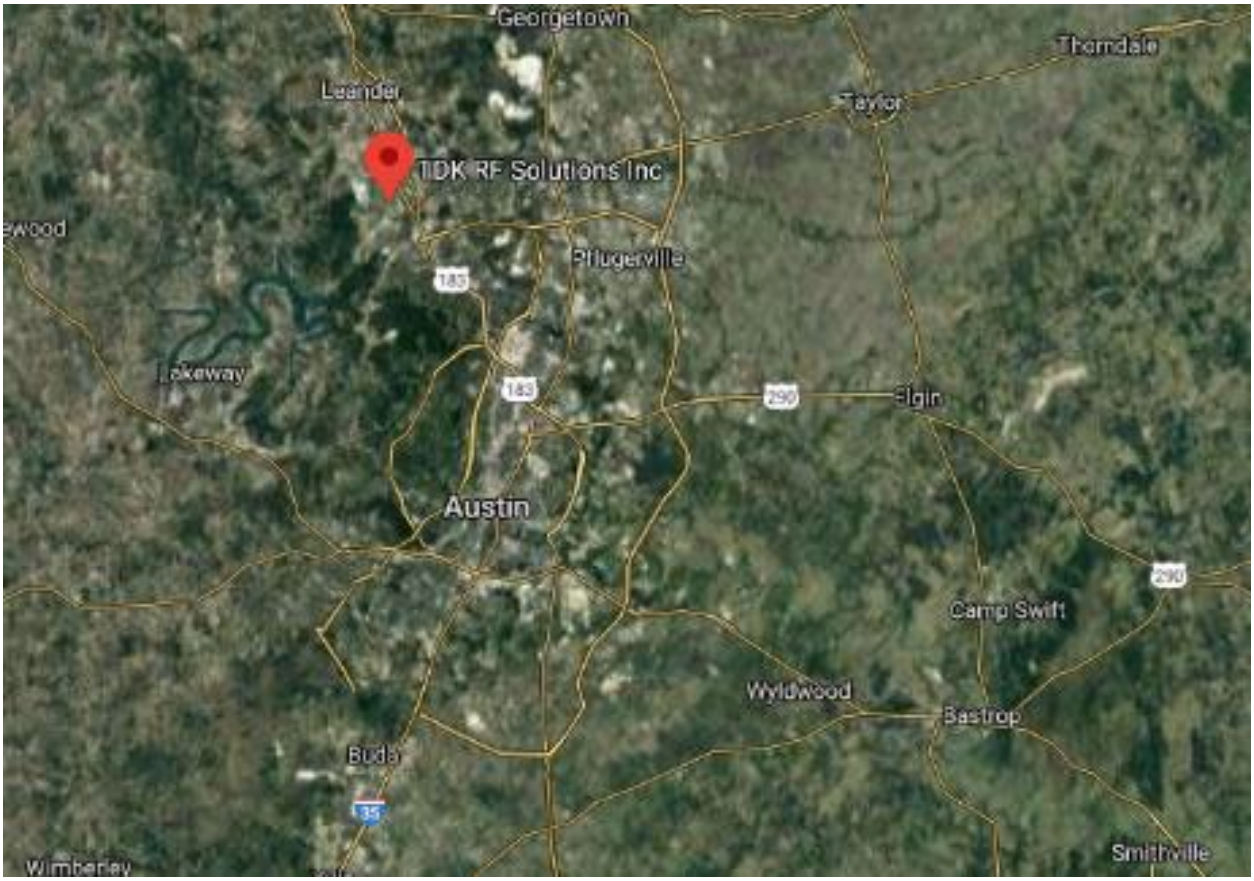


Figure 28: Overview map of location of TDK RF Solutions OATS

According to the United States Census Bureau, Cedar Park had an estimated population of 76999 in July 2018 [17]. Its population density is based on census data in 2010 and was 2,141.9 people per square mile (~827 people per square kilometre). According to the U.S. FCC's Universal Licensing System, as of 12 February 2020 there are 342 active amateur radio licenses registered in Cedar Park corresponding to 0.44% of the estimated population.

In order to characterize the peak ambient RF conditions at the TDK RF Solution's site, a calibrated loop, as defined in CISPR 16-1-4 [65], was used to record radiated emissions measurements at various times of the day and with various antenna orientations. The results of the ambient emissions with this antenna is shown below combined with standardised and proposed emission limits. The extrapolations are based on the principle that the magnetic field strength decays at a 20 dB/decade rate in the far-field region of a radiating source and decays at a rate of 60 dB/decade within the near-field region. The current limits as outlined in CISPR 11 edition 7 [6] and IEC 61980-1 [7] are also shown in the charts for comparison. Standard CISPR settings utilizing a resolution bandwidth (RBW) of 200 Hz from 9 kHz to 150 k Hz and a RBW of 9 kHz from 150 kHz to 30 MHz was used for EMC assessment and ambient peak correlation to collect the data. It should be noted that the ambient data collected represents peak data as seen at the receiver (using the CISPR peak detector) including local ambient transmission bursts and some "time-varying narrow-band signals". The peak ambient data does not represent the man-made radio noise floor as outlined in Recommendation ITU-P.372-17 [25], which is based on median values of man-made noise for the given environment. It has been suggested by several more recent studies e.g. carried out by the University of Twente in the Netherlands [81] and the Basque University in Spain [27], however, that the man-made noise floor in the MF and HF band has risen in recent years. For a complete comparison of measured data, EMC limits and noise floor levels, the chart below shows a comprehensive summary including the Recommendation ITU-P.372 [25], median man-made noise factors converted to magnetic field strength (in dBµA/m) assuming a monopole antenna. It also includes the Recommendation ITU-P.372 [25], value updates as suggested in [26], peak ambient conditions and measured peak system receiver noise.

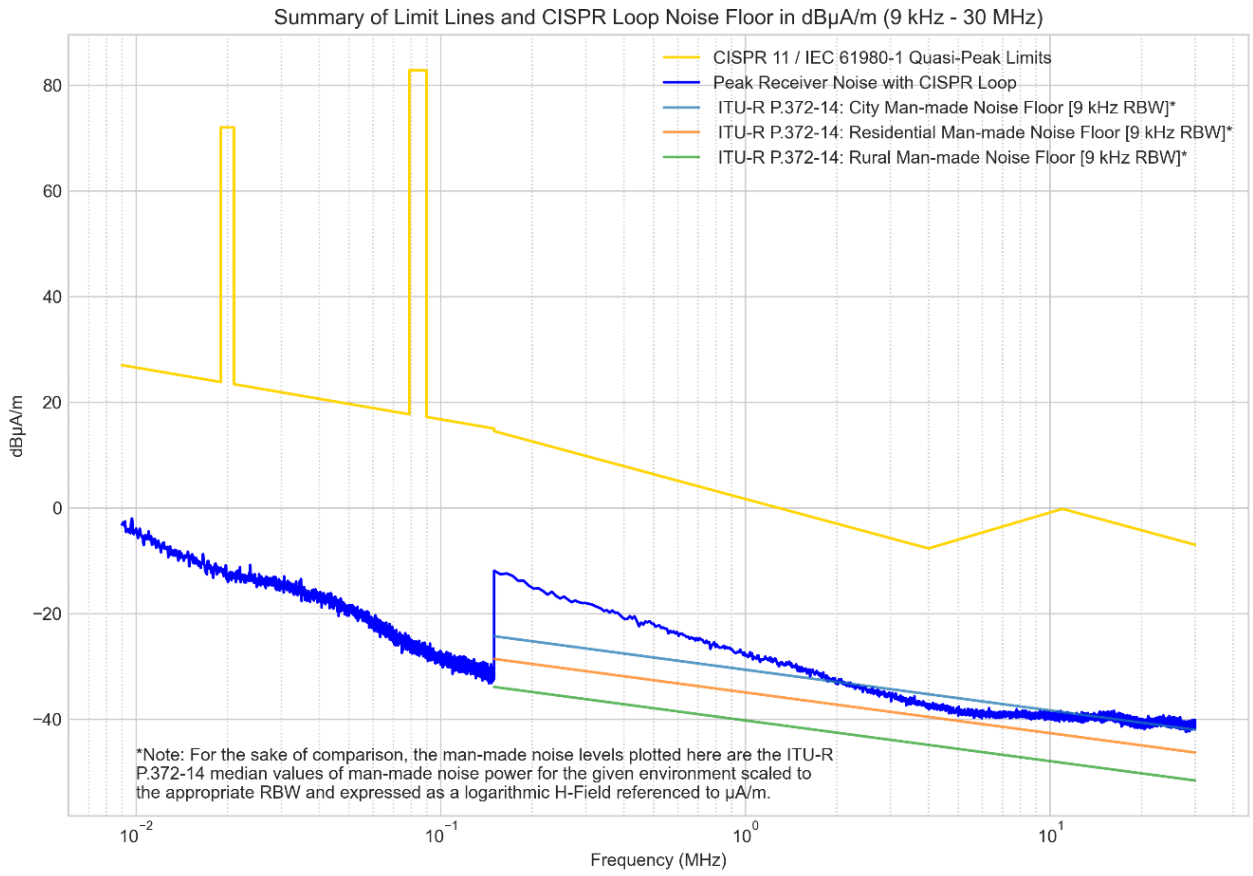


Figure 29: Overview of limits and system noise with CISPR loop, as well as converted Recommendation ITU-R P.372 man-made noise levels and suggested IEEE paper updates based on different noise measurement procedures as outlined in Recommendation ITU-R SM.1753 [49] (i.e. statistical, non-peak measurements)[4]

Note: The Recommendation ITU-P.372-17 [25], and IEEE referenced levels are included for informational purposes; however, it is important to note that the measurement procedures for the quasi-peak measurements and the Recommendation ITU-P.372-17, man-made noise measurements and procedures are very different as outlined in Recommendation ITU-R SM.1753 [49].

For a direct comparison of only the system receiver noise with the TDK CISPR 60 cm loop antenna used in measurements and other commercially available antennas, the plot below is from a study conducted by CISPR B in CIS/B/736/INF [30] using the same RBW settings (200 Hz RBW from 9 kHz to 150 kHz and 9 kHz RBW from 150 kHz to 30 MHz). It should be noted that only a small subset of the available loop antennas was measured in the study conducted by CISPR. As indicated below in one example, there may be other more sensitive (e.g. ~10 dB more sensitive) CISPR loop antennas available.

[4] Class B CIS/B/737/CDV was rejected in CISPR.

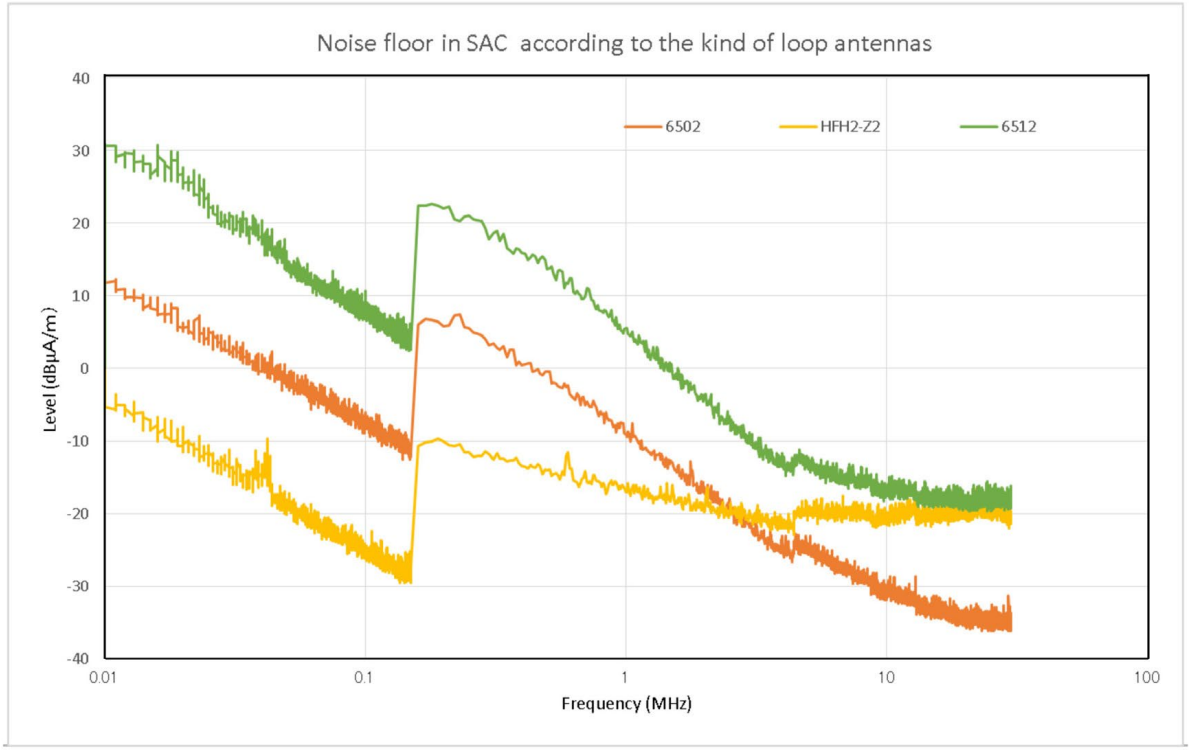


Figure 30: System noise measurements with various system loops as performed by CISPR B and reported in CIS/B/736/INF

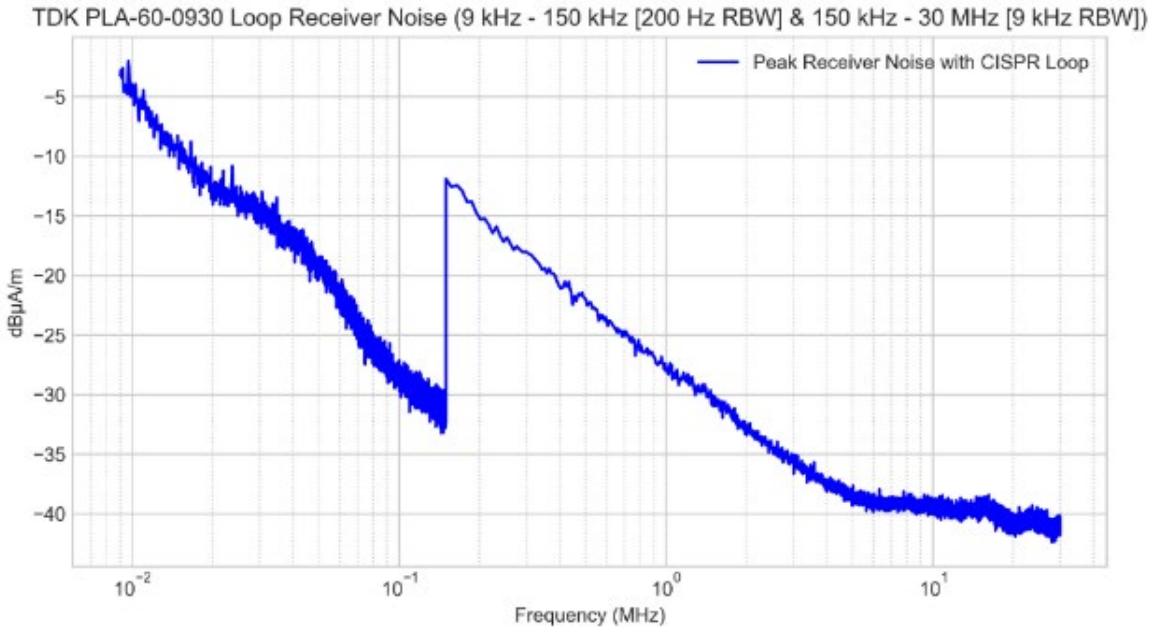


Figure 31: System noise measurements with the TDK PLA-60-0930 CISPR Loop used for measurements in this impact study

The following plots show peak ambient emissions at the OATS to assist in visually identifying peaks related to the WPT-EV system tested versus ambient peaks present at various times during testing. Plots are given in consideration with orientations in X & Y being coaxial and coplanar respectively to the location of the EUT (i.e. perpendicular from ground plane) as well as the Z orientation with the loop being horizontal (i.e. parallel with ground plane).

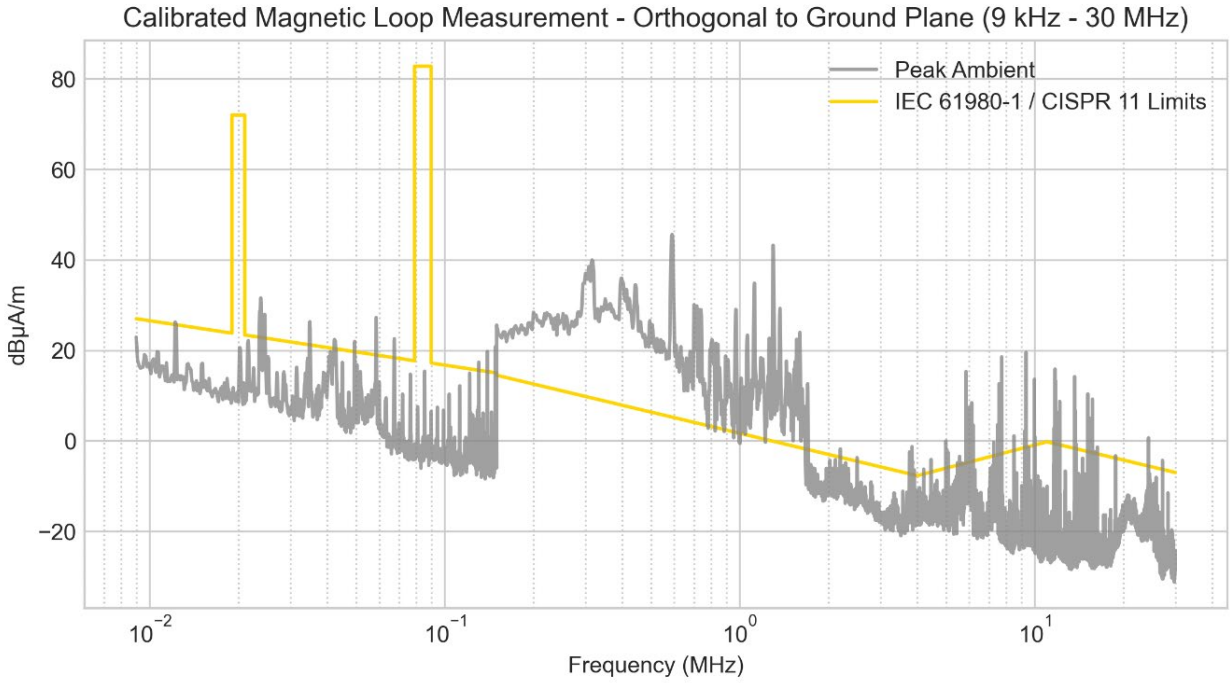


Figure 32: Ambient peak measurements on the OATS with calibrated magnetic loop orthogonal to the ground plane peak measurements)

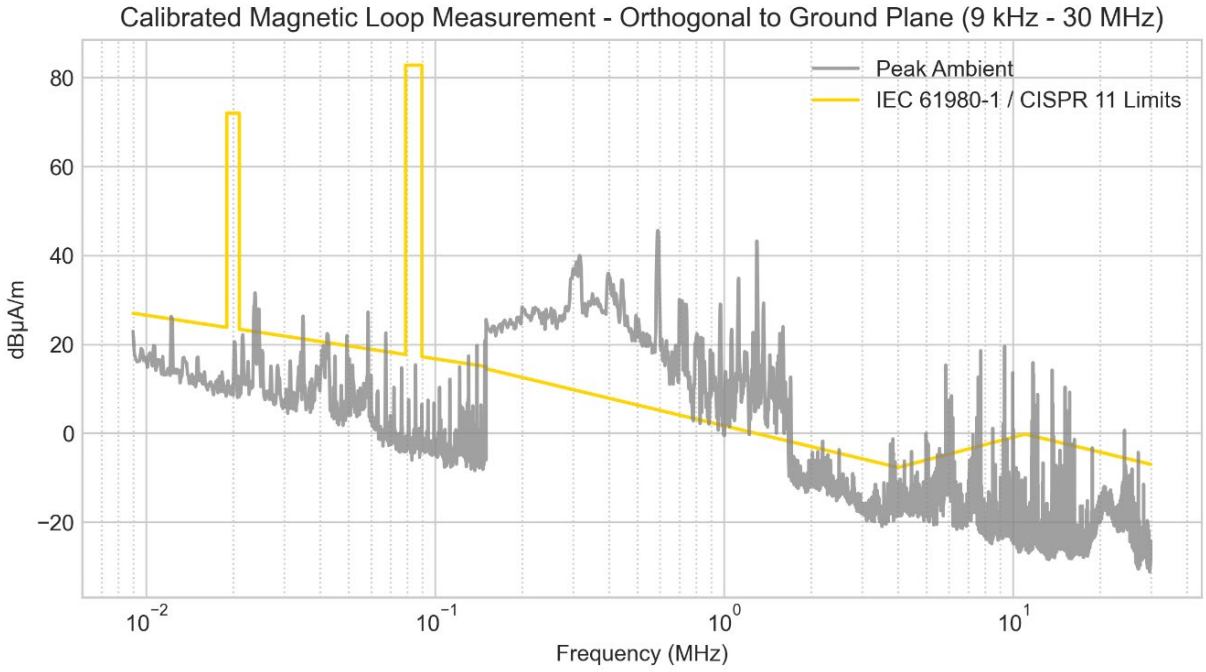


Figure 33: Ambient peak measurements on the OATS with calibrated magnetic loop parallel to the ground plane peak measurements)

To assess relative ambient conditions using standard amateur radio equipment, a typical portable monopole antenna (quite a bit larger than the calibrated monopole) capable of operating from the 80 m amateur band to the 6 m amateur band was also used (see § A1.3.3 for measurement equipment list). The spectrum analyser

trace was set in a max hold mode measuring from 150 kHz to 30 MHz with 9 kHz RBW, 30 kHz VBW and 40001 points.

In each of the bands, a marker indicates where a projected WPT-EV harmonic could potentially occur (though the WPT-EV system was not operating during the measurements). It is noted that the measurement conditions using a CISPR peak or peak-hold detector for standard EMC limit evaluation are not the same as the measurement conditions used to measure man-made noise floor levels that are indicated in Recommendation ITU-P.372-17 [25], which are derived using measurement techniques outlined in ITU-R Recommendation ITU-R SM.1753 [49]. The intent of the ambient measurements made with a typical amateur radio monopole are to assess the relative differences seen at the radio receiver with the WPT-EV system OFF (peak ambient emissions) and ON (peak ambient + WPT-EV system emissions) and to ensure capture of all time varying and rotationally dependent peaks emanating from the WPT-EV system in comparison with ambient emissions otherwise present. It should be noted, however, that peak-hold measurements maintain the maximum peak of time-varying signals or noise that can, in turn, mask noise floor conditions. This is particularly true in a location where any impulse or time-varying noise is present. The OATS location in Cedar Park, Texas abuts a residential neighbourhood to the west and business complexes to the north and south. The location of the OATS could generally be described as a light-business area with offices and small businesses in operation during testing. The site complies with the ANSI C63.7 (which is equivalent to EN 55016-1-4 [67] for site validation) construction methods for EMC measurements, requiring among other criteria, that the site be located a minimum distance away from obstruction-free areas that could perturb the measurements.

In Figure 37 and associated charts found within this study, ambient noise consists of both wanted radio service emissions and unwanted ambient emissions present in the environment unrelated to the WPT-EV system under study. The charts show the voltage in dBµV as it would be presented to a 50 Ω radio receiver due to the ambient peak noise. It should be noted that Figure 34 is highly compressed as it covers a wide range of frequencies. Subsequent charts show zoomed in portions of Figure 35 in the amateur radio bands. The red dots represent where potential WPT-EV harmonics could potentially occur, but the WPT-EV system is not operating in Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38.

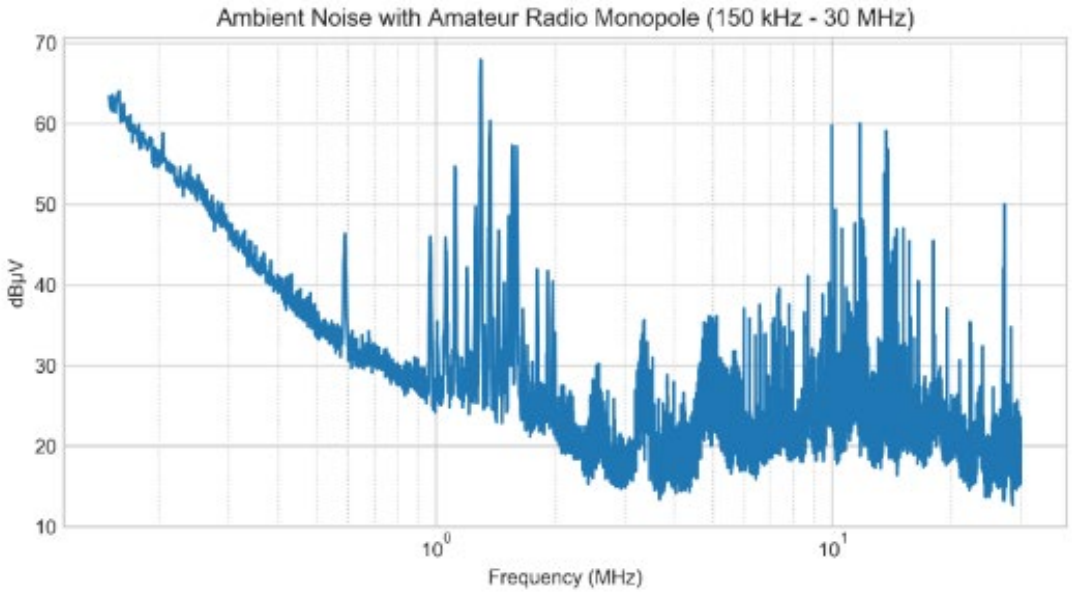


Figure 34: Ambient noise with amateur radio monopole

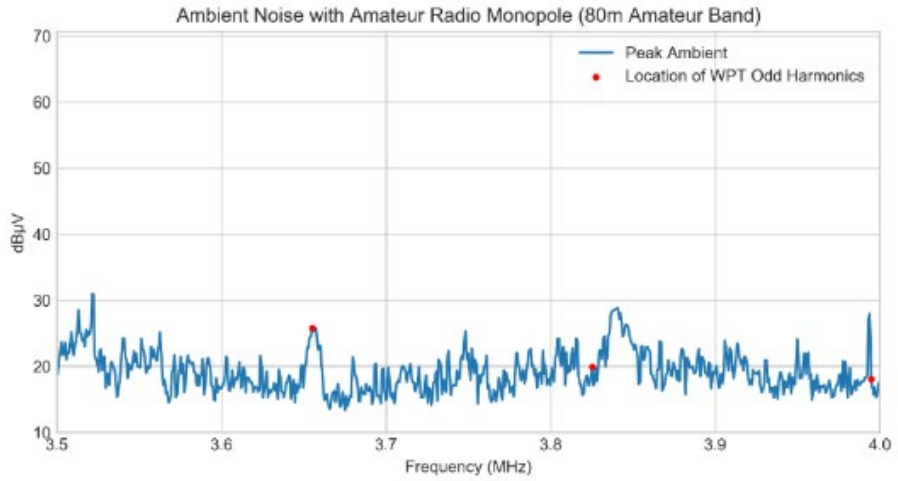


Figure 35: Peak ambient seen at receiver using the amateur radio monopole antenna (80 m band)

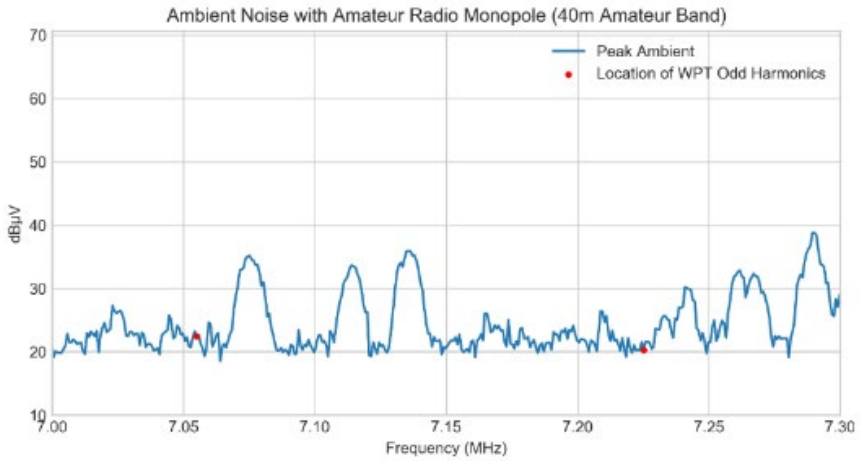


Figure 36: Peak ambient seen at receiver using the amateur radio monopole antenna (40 m band)

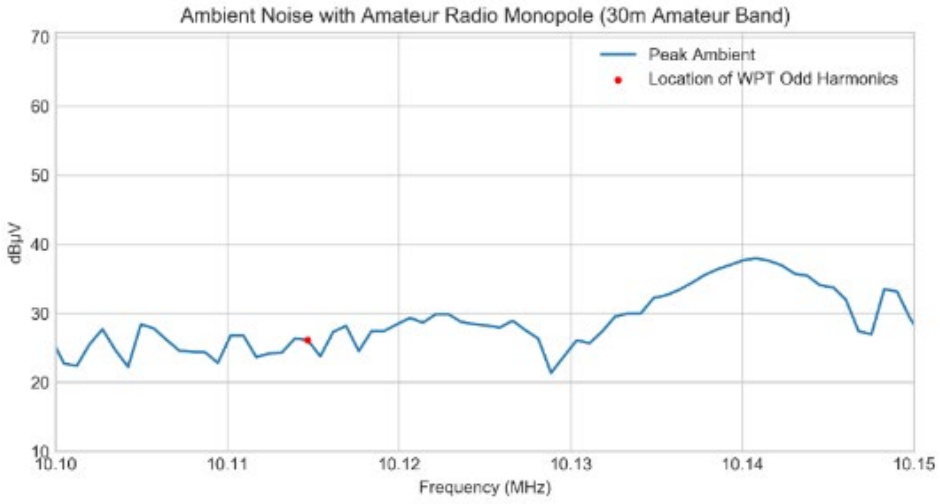


Figure 37: Peak ambient seen at receiver using the amateur radio monopole antenna (30 m band)

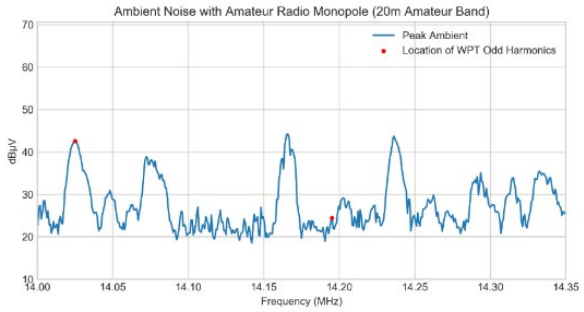


Figure 38: Peak ambient seen at receiver using the amateur radio monopole antenna (20 m band)

It was noted by a test observer that the ambient conditions of the test site seemed high and therefore additional ambient measurements were taken in a more rural part of the United States in Nibley, Utah to compare relative conditions that an amateur radio operator may experience. Census data from 2010 on Nibley, Utah shows its population density was 87.4 people per square mile (226.4 people per square kilometre). The FCC's ULS database shows 44 amateur operators with active licenses registered in Nibley, Utah as of 12 February 2020. A comparison of relative peak ambient measurements as seen at the receiver (not converted to field levels) using the amateur radio monopole from 150 kHz to 30 MHz is shown below with zoomed conditions in each of the measured amateur radio bands. The duration of the peak hold measurements was in the range of 5 to 15 minutes just before midday. It is however difficult to draw complete conclusions of the noise environments at different sites when using long-term peak-hold.

The location of measurement in Nibley, Utah occurred in a local residential field with a local business and school approximately 75 meters north and west of the measurement point. The measurements in Nibley, Utah were performed approximately 10 meters from the office where the measurement equipment resides. At the time of measurement for the Nibley, Utah data, the school and businesses within a 75 metres radius were not operating due to local economy shutdown. Amateur stations could be located in the residential portion of either location, so these tests are representative of what could be found in a range of amateur stations. It must be noted, however, that comparisons between EV harmonics at the two locations being measured can be applied only to the locations with similar ambient noise and signal levels.

Figure 39 shows a combination of radio signals and noise over a large frequency range and therefore the features in the chart are very compressed. Zoomed-in portions of the amateur frequency bands are shown in the subsequent figures derived from the data shown in Figure 39.

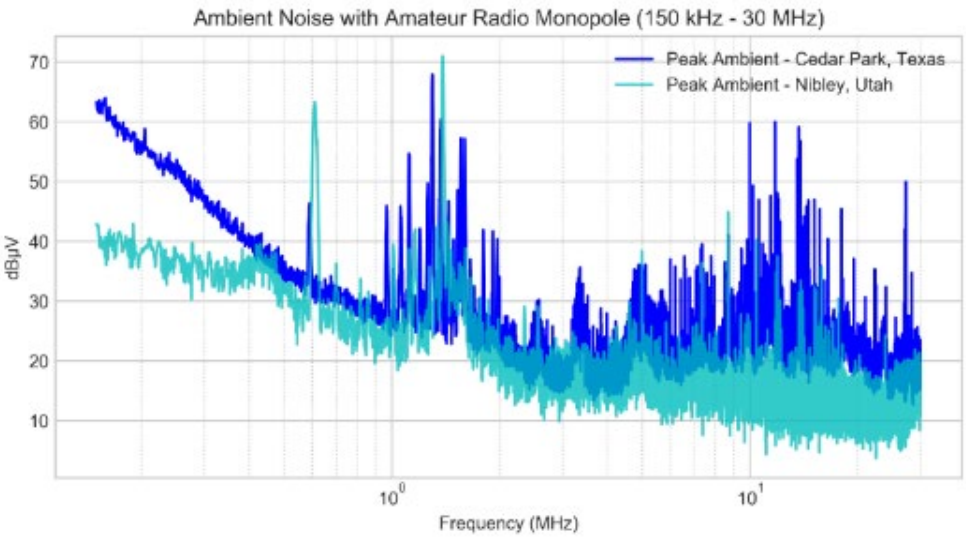


Figure 39: Peak ambient comparison between two locations seen at receiver using amateur radio monopole antenna

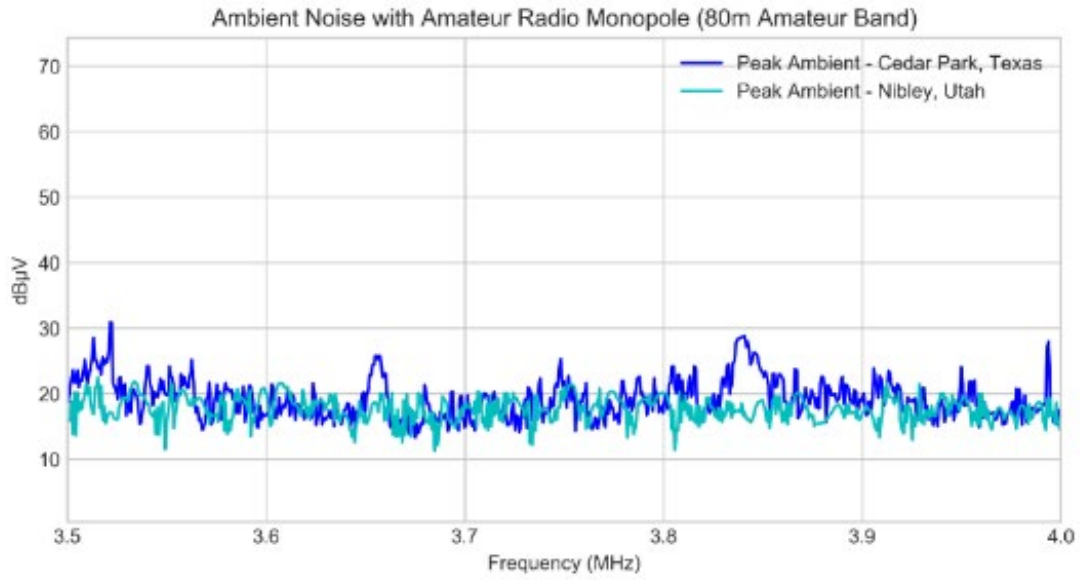


Figure 40: Peak ambient comparison between two locations seen at receiver using amateur radio monopole antenna (80 m band)

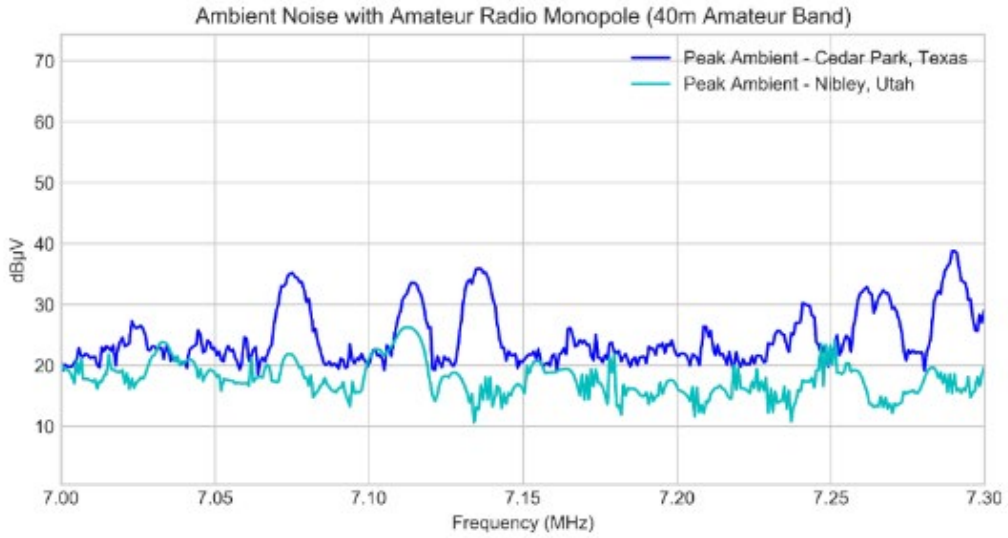


Figure 41: Peak ambient comparison between two locations seen at receiver using amateur radio monopole antenna (40 m band)

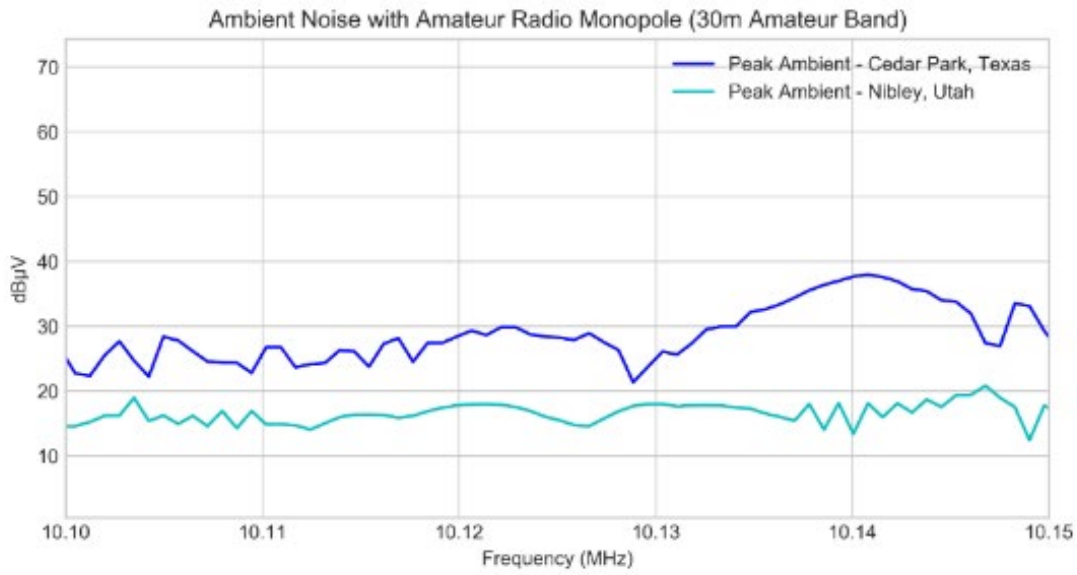


Figure 42: Peak ambient comparison between two locations seen at receiver using amateur radio monopole antenna (30 m band)

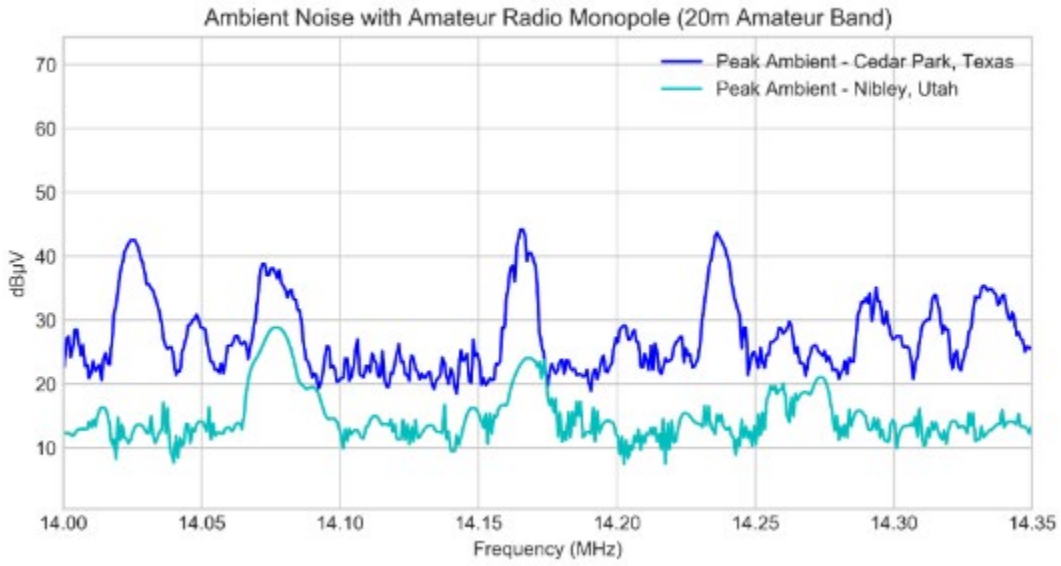


Figure 43: Peak ambient comparison between two locations seen at receiver using amateur radio monopole antenna (20 m band)

As can be seen, the ambient conditions between these two distant locations (separated by ~1300 miles or ~2100 km), the peak-hold ambient measurements in the 80 m and 40 m bands showed similar characteristics, whereas in the 30 m and 20 m bands, the levels in Nibley, Utah were on average ~10 dB lower than those in Cedar Park, Texas. A satellite image of Nibley, Utah is shown below for comparison.



Figure 44: Satellite map view of Nibley, Utah

While it is generally expected that ambient conditions would be even lower in un-populated areas of the U.S. (e.g. forests, mountains, fields, etc.) where several amateur radio operators have been setting up portable stations for low-noise conditions, it is not expected that WPT-EV systems would be generally located nearby (e.g. much greater than 30 m) in such areas.

After testing, additional questions were raised as to the levels of ambient emissions shown in previous figures and whether the test environment is typical to those in which a WPT-EV system would operate (e.g. residential / commercial). The peak-hold ambient figures shown cannot be compared to the Recommendation ITU-P.372-17 ITU-P.372 [25], man-made noise (MMN) levels because the measurement methods for MMN, containing white-gaussian noise (WGN) and some periodic impulse noise (IN) (with all galactic noise removed), are very different from those used for measuring single-carrier noise (SCN) such as harmonic emissions from WPT-EV. More particularly, there has been suggestion that the background ambient noise plots in Annex 12 might be abnormally higher than typical residential and commercial environments since the apparent noise levels in the plot are higher than the man-made noise (MMN) levels indicated in Recommendation ITU-P.372. This comparison is incorrect because levels in Recommendation ITU-P.372 are based on statistical median measurements of white-gaussian noise (WGN) with some periodic impulse noise (IN) included. All single-carrier noise (SCN) and locally identifiable impulse noise (IN) and galactic noise is removed from the MMN levels as indicated in Recommendation ITU-R SM.1753 [49], which includes the basis for the Recommendation ITU-P.372-17 MMN levels. Furthermore, these Recommendation ITU-R P.372 measurements are taken over several seasons and across 24-hour periods to obtain the statistical results. For comparison of understanding, it is important to note that Recommendation ITU-R P.372 [25] MMN has the following distinct characteristics in the spurious bands of interest below 30 MHz:

- Recommendation ITU-P.372-17 represents ONLY WGN (not SCN) and Recommendation ITU-R SM.1753 clearly indicates that both SCN and WGN are important. Recommendation ITU-R SM.1753 also clearly states that “it is virtually impossible to find a location that is not at least temporarily dominated by noise or emissions from a single source…” and that “it may be unrealistic to exclude these components from radio noise measurements.” Recommendation ITU-R SM.1753 also indicates that “Recommendation ITU-P.372-17 specifically excludes emissions from single, identifiable sources.” Recommendation ITU-R SM.1753 reiterates how important both the SCN and WGN are to radio by noting that, “radiocommunications have to cope with all unwanted signals, whether it is noise or interference, to function properly. For practical reasons it may therefore be desirable to measure the sum of both.” Particularly in the HF band, it also notes that, “In the HF frequency band, it is virtually impossible to find a frequency that is free of wanted emissions for the whole 24 h measurement period”;

- The Recommendation ITU-P.372-17 [25] values that are being referenced are based only on man-made noise (MMN) which specifically removes any natural environmental effects. More particularly, Recommendation ITU-R SM.1753 [49] states that "Even on one frequency the radio noise level, especially when dominated by MMN, varies depending on time and location. In frequency bands below 30 MHz, noise levels mainly change over time due to propagation conditions";
- The Recommendation ITU-P.372-17 WGN MMN values below 30 MHz are based on median values of measurements which occurred in at least 10 locations over 24-hour periods and across multiple seasons. Specifically, in Recommendation ITU-R SM.1753, it states that in addition to a standard measurement period of 24 hours, it is important "To take into account variation due to seasons, HF measurements may be repeated a number of times each year." This is noteworthy considering that HF propagation conditions change frequently;
- The Recommendation ITU-P.372-17 WGN MMN values are based on RMS measurements – not peak. The Recommendation ITU-P.372-17 values do not represent the only source of noise and clearly do not represent the dominant source of noise, which is SCN as also indicated in Recommendation ITU-R SM.1753 [49].

The previous comparisons made were done using peak measurements (using methods described in Recommendation ITU-R SM.329, annex 2 [13]) as seen by the amateur radio receiver but measured with a spectrum analyser; however, some additional measurements were taken by TDK RF Solutions of the ambient environment using similar metrology (described in Recommendation ITU-R SM.1753) to that used to measure MMN in Recommendation ITU-P.372-17. This is shown below for reference and shows an underlying noise level some 20 dB lower than in the figures taken with peak-hold measurements.

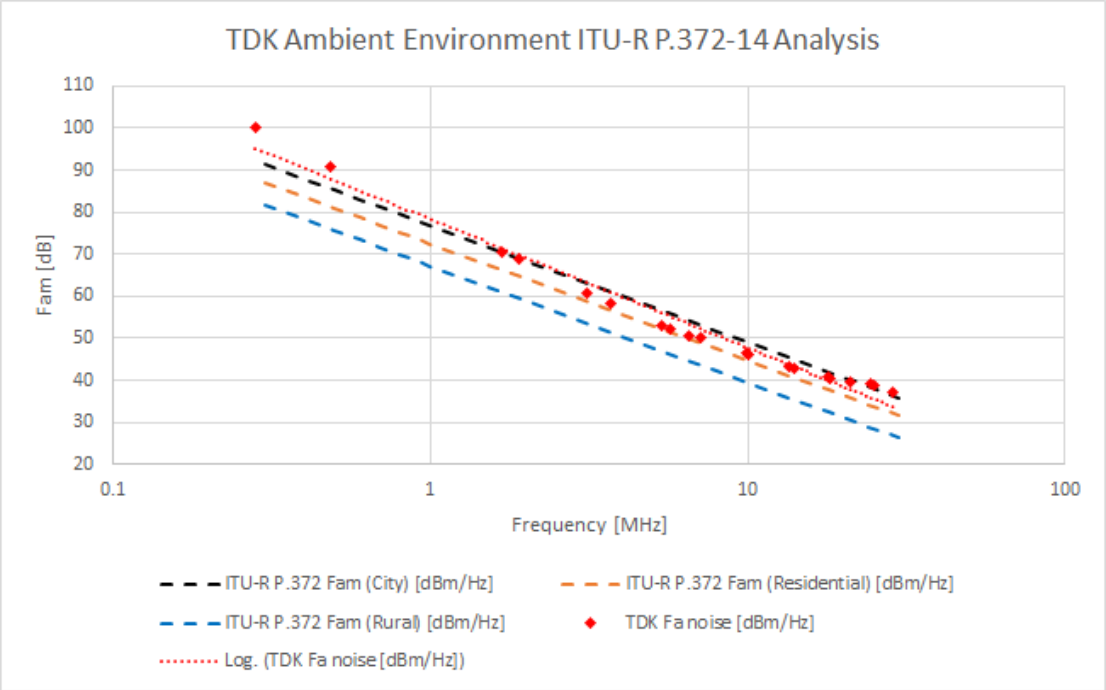


Figure 45: Additional TDK WGN Ambient Measurements

The primary differences in the measurement done by TDK for this plot and the method described in Recommendation ITU-R SM.1753 [54] included the following:

1 these measurements were taken using a standard CISPR loop antenna rather than a monopole antenna;

2 these measurements were taken over a short period of time only (during the day only when the levels are expected to be highest);

3 these measurements were taken in only one season (close to the time period of the original study);

4 these measurements were taken only at the single site and do not include other locations.

These additional measurements taken at the accredited OATS are for reference only and are not definitive by themselves. It should be noted that the use of the word "ambient" in the context of Figure 28 is different than the usage in other peak and quasi-peak measurements due to the method of measurement (i.e. metrology) being different. The term "ambient" thus depends heavily on its context and should not be the sole basis for understanding environmental noise, which includes many different sources with different characteristics and time-varying behaviour.

The conclusion that the ambient environment noise is typical of a residential environment is further supported by independent data and tests [32]. In a separate study performed entirely independently by Swiss amateur radio experts from USKA and Brusa [33], using a different WPT-EV system operating in a residential Switzerland neighbourhood, ambient environment measurements were also taken and compared with those taken in Cedar Park Texas, U.S.A. These measurements taken in Ersigen, Switzerland next to an amateur radio station in a residential neighbourhood were also taken using the standardised CISPR EMC settings as is typical globally for such measurements (and as described in Recommendation ITU-R SM.329, annex 2 [13]). In the USKA/Brusa study [34], the independent assessors reference the data from the contributed U.S. study and provide the following peak-hold comparison plot for review. It should be noted, however, that the ambient comparison measurements in peak-hold and are entirely unrelated to the man-made noise measurements shown in Recommendation ITU-P.372-17 [25] and the measurement procedures indicated in ITU-R SM.1753 [49].

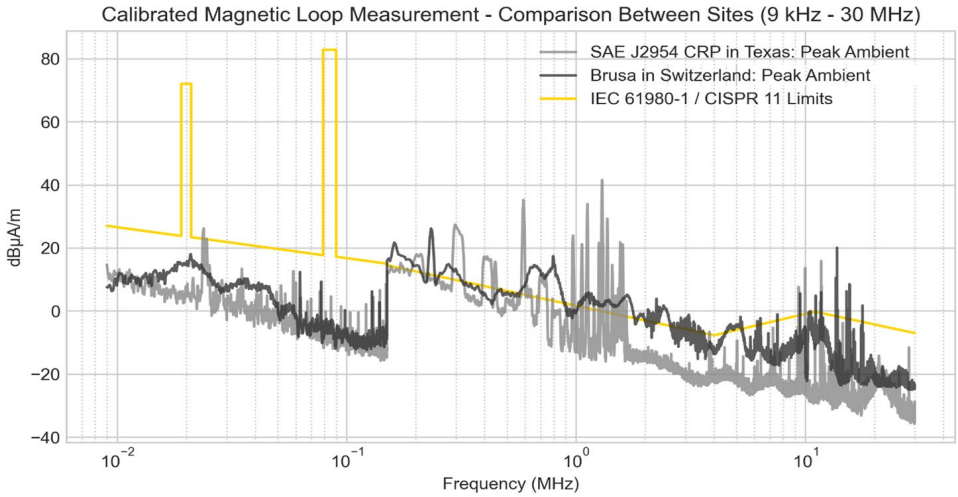


Figure 46: Ambient comparison measurements performed in a separate study [33],[34]

A1.4.3 Measurement Equipment, Measurement Standards and Measurement Setup

The same calibrated spectrum analysers used for the standardised EMI testing were also used to measure the spectrum as seen using the different amateur radio antennas as well.

Calibrated Equipment for Radiated Emissions Testing:

- Keysight Technologies (formerly Agilent Technologies) MXE Spectrum Analyzer;
- Rhode and Schwarz ESCI EMI Test Receiver;
- Rhode and Schwarz ZNL3 Vector Network Analyzer (VNA);
- TDK RF Solutions Magnetic Loop Antenna PLA-60-0930;
- A.H. Systems Monopole Antenna SAS-551;
- TDK RF Solutions Accredited Open Area Test Site.

Calibrated Equipment for EMF Testing:

- Narda ELT-400 Field Probe;
- TDK RF Solutions Automated Robotic Positioning System.

Radiated Emissions Interference Testing:

- Alpha Antenna HD-FMJ 6-80 Meter Portable HF Antenna (~20 ft / ~6 m tall);
- Chameleon V1 HF 6-80 Meter Vertical Dipole Antenna raised ~20 ft (~6);
- Yaesu 857D HF/VHF/UHF Transceiver;
- Airspy HF+ Discovery Software Defined Radio with SDRSharp Software Interface.

Figure 47 is the WPT-EV test setup on the OATS for calibrated radiated emissions testing.



Figure 47: Setup on OATS for calibrated radiated emissions testing

Figure 48 is the WPT-EV test setup in a typical garage setting for calibrated EMF exposure testing.

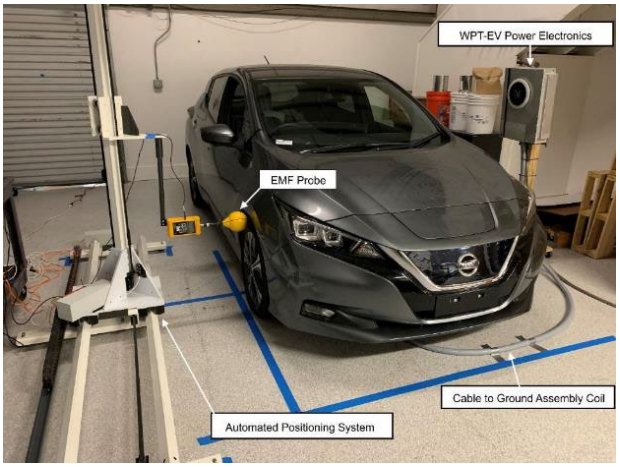


Figure 48: Setup over in garage with concrete floor for calibrated EMF measurement testing

The amateur radio antennas (Chameleon V1 vertical dipole and HD-FMJ monopole) were setup over real earth at 10 m, 20 m and 30 m distances from the WPT-EV system on the OATS and turn table. The turn table was rotated to obtain worst-case conditions. While two types of antennas were initially used (both a vertical dipole and monopole), the qualitative results from the two antennas appeared similar and the vertical dipole was determined to be less sensitive so all remaining data was collected using the HD-FMJ monopole which was a much simpler setup for measurement. These two antenna types and the setup conditions for 10 m, 20 m and 30 m distances are shown below.



Figure 49: Setup of amateur radio vertical dipole antenna at a distance of 10 m from WPT-EV system



Figure 50: Setup of amateur radio monopole antenna at a distance of 10 m from the WPT-EV system



Figure 51: Setup of amateur radio monopole antenna at a distance of 30 m from the WPT-EV system



Figure 52 Setup of amateur radio monopole antenna at a distance of 30 m from the WPT-EV system:

The amateur radio monopole antenna has multiple configurations for changing the characteristics of the antenna e.g. by adding a line for NVIS (Near Vertical Incidence Skywave) transmission and reception. Because the amateur radio antennas have not been specifically calibrated for absolute field strength measurements, all measurements shown are relative. The plots below show an S-parameter (S11) characterisation of the amateur radio monopole antenna with and without the NVIS line.

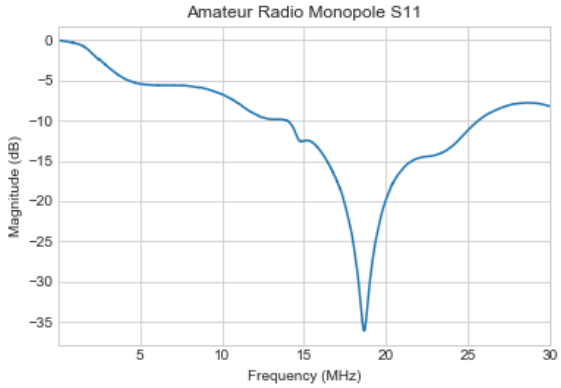


Figure 53: S11 measurements of amateur radio monopole antenna

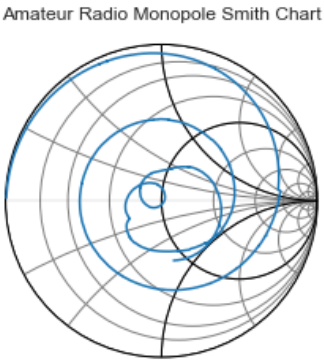


Figure 54: Smith chart for measurements of amateur radio monopole antenna

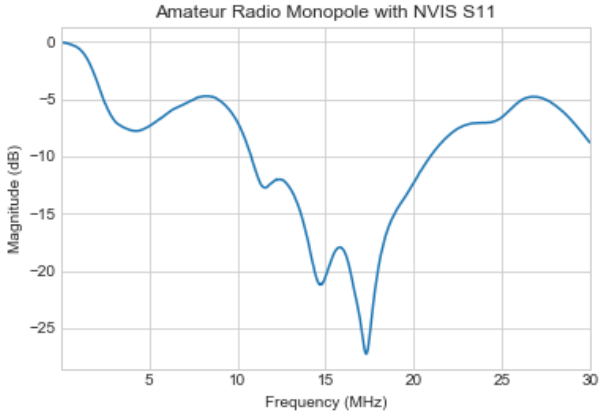


Figure 55: S11 measurements of amateur radio monopole antenna with NVIS line

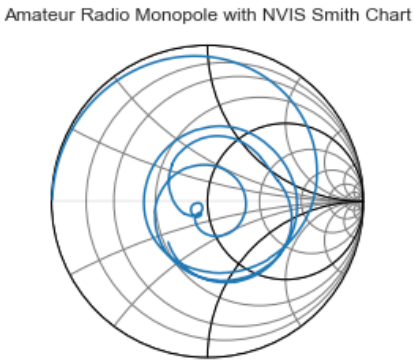


Figure 56: Smith chart for measurements of amateur radio monopole antenna with NVIS line

A1.4.4 Measurement Results

A1.4.4.1 Radiated Emissions Measurement Results

Calibrated Testing with Magnetic Loop Antenna

A calibrated CISPR-16-1-4 [70] 60 cm magnetic loop was used to perform radiated emission measurements from 9 kHz to 30 MHz on the OATS. The WPT-EV system was turned on to charge the EV with ~11 kW of input power at efficiencies around 90% AC grid input to DC battery output. The state of charge of the EV ranged from ~25% to 85% during testing to ensure that the power level was maintained constant, but the battery voltage changed overtime. Within this range, these variations in charge level and battery voltage did not significantly affect emissions for the WPT-EV system evaluated. The EV battery capacity was specified at 62 kWh. The WPT-EV alignment between the ground coil and the vehicle coil were put in worst-case offset conditions at the specified 175 mm ground height (referring to the ground-to-vehicle pad distance if the vehicle were to be on the road) to ensure the highest current and the most exposed coil conditions possible. Due to the fact that the WPT-EV system was a pre-production prototype, it was not expected to fully comply with present radiated emission standard requirements such as CISPR 11 [6] and IEC 61980-1 [7] in all cases; however, this testing is considered generally representative for an SDO conformant WPT3 WPT-EV system.

To capture maximum emission peaks in the spectrum scans, the turn table with the WPT-EV system was rotated in 2 degree increments across the entire 360 degree rotation and for each loop orientation (e.g. x, y, z axis). From 9 kHz to 150 kHz, the resolution bandwidth was set to 200 Hz and from 150 kHz the resolution bandwidth was set to 9 kHz as defined by standardised EMI measurement procedures. To obtain more detailed results for the fundamental and harmonically related peaks in the amateur radio bands, the resolution

bandwidth was set to 200 Hz and the turn table rotated in 2 degree increments to find the maximum condition to perform quasi-peak and average measurements as well as obtain a polar radiation plot.

Below are the maximum peak scans with ambient measurements collected separately (and hence not necessarily time-correlated) for relative comparison. The current 7th edition of CISPR 11 limits as outlined in IEC 61980-1 [7] are also shown in the charts for comparison.

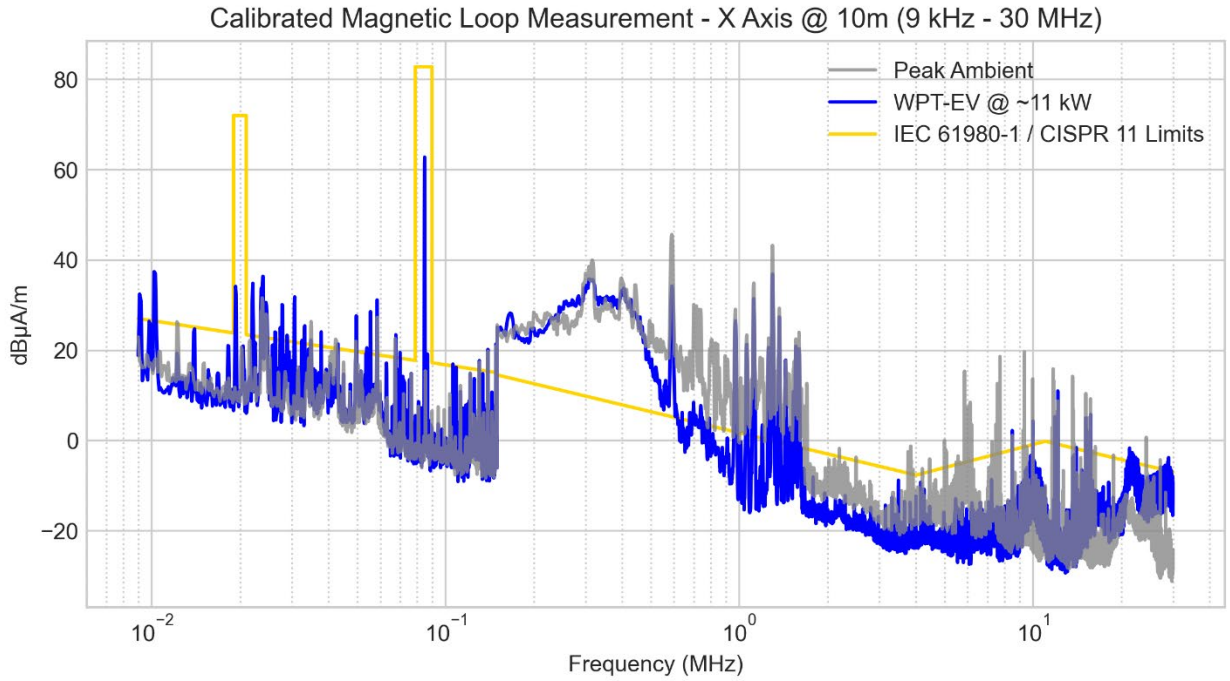


Figure 57: Calibrated magnetic loop measurements in X-axis (loop coaxial to EUT) with WPT-EV system on and off for comparison

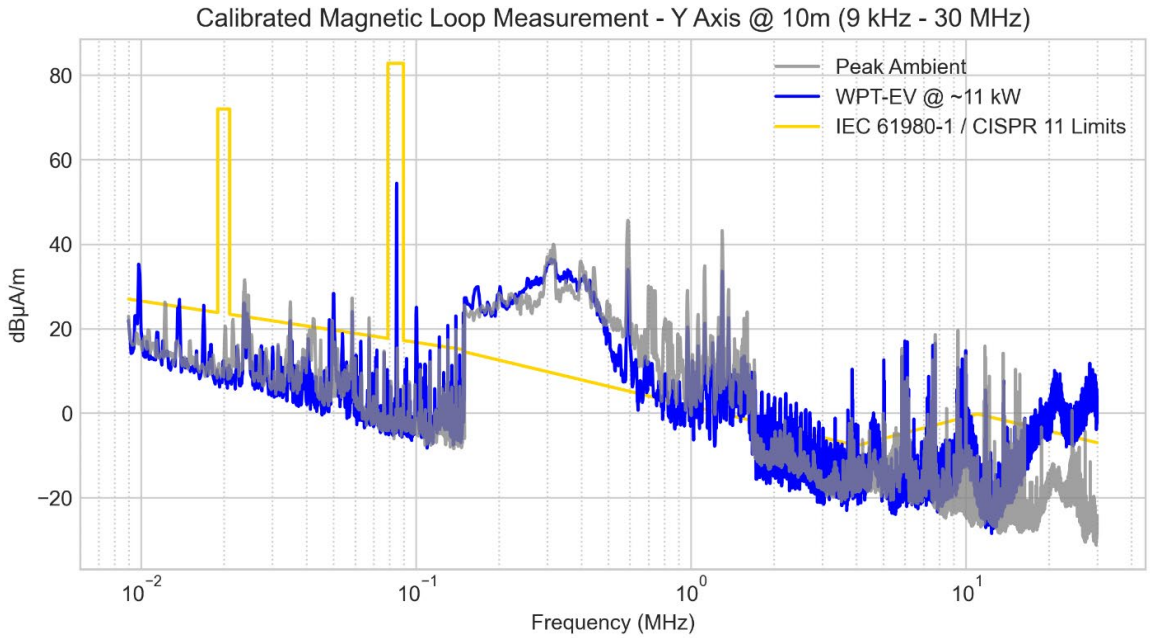


Figure 58: Calibrated magnetic loop measurements in Y-axis (loop coplanar to EUT) with WPT-EV system on and off for comparison

The increased broadband noise level at frequencies above 15 MHz is attributed to an auxiliary low power switched-mode power supply and is not fundamentally related to the WPT-EV core system.

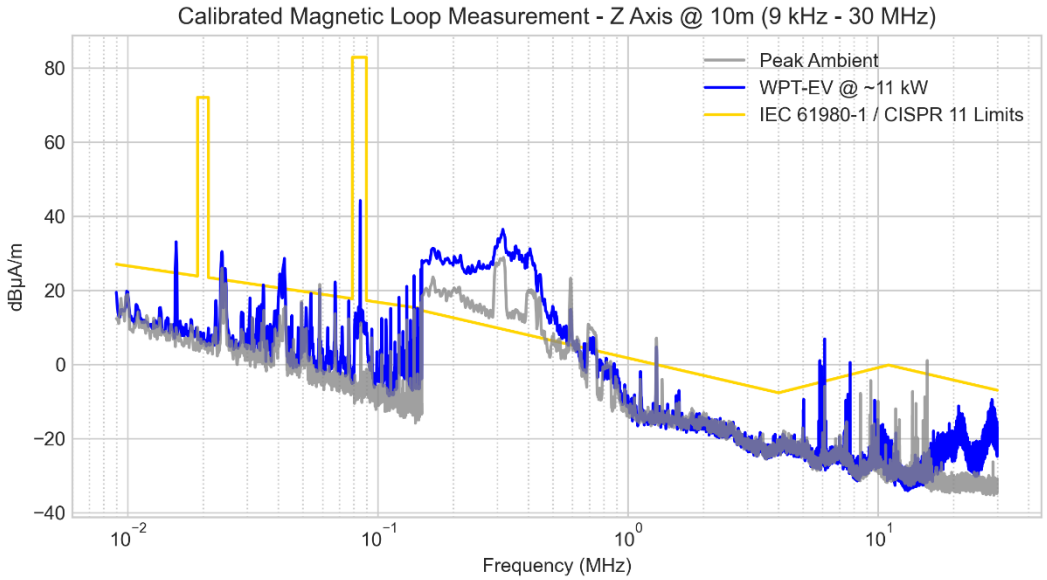


Figure 59: Calibrated magnetic loop measurements in Z-axis (loop parallel to ground) with WPT-EV system on and off for comparison

A zoomed in view of the 85 kHz fundamental as well as the 80 m, 40 m, 30 m and 20 m amateur radio bands are shown below along with the measured quasi-peak and average values. It should be noted that the specifically annotated values in the plot were collected with a much lower RBW (i.e. 200 Hz) than the continuous plots which utilised a higher RBW (i.e. 9 kHz) as prescribed by CISPR. Only peaks that appeared to be somewhat discernible at a low-resolution bandwidth were collected though some of the peaks were barely above ambient conditions. Narrowband signals (with respect to the selected CISPR RBW) being essentially continuous wave (CW) signals and displaying sufficient signal to noise ratios will produce essentially the same amplitude response for peak, QP (quasi-peak), or AVG (average) detectors. It is noted based on subsequent qualitative measurements, that the results of these measurements show that the WPT-EV system has minimal interference potential to stations operating in the noise levels present at the OATS. For quieter locations, additional measurement would be required to ascertain interference potential (at expected distances between a WPT-EV system and receiver) in such environments.

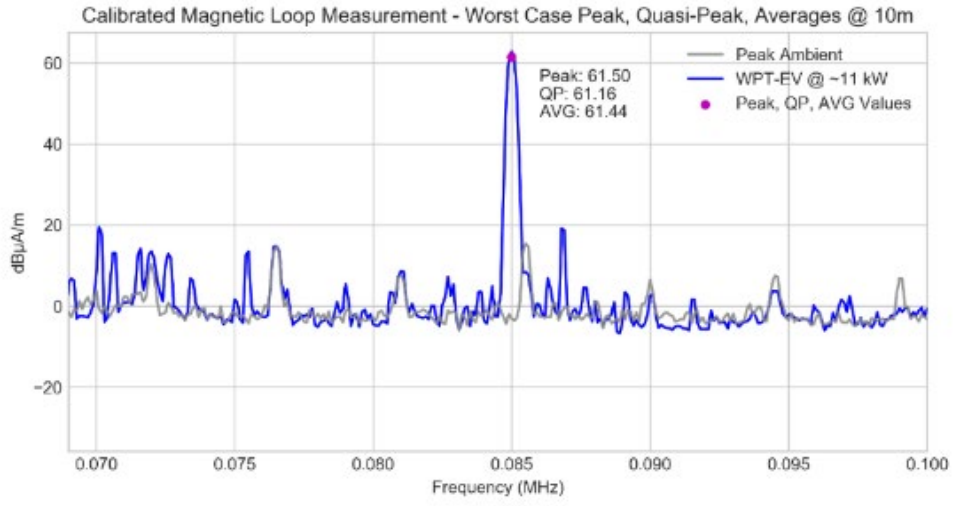


Figure 60: Detailed worst-case calibrated magnetic loop measurements with WPT-EV system on and off for comparison

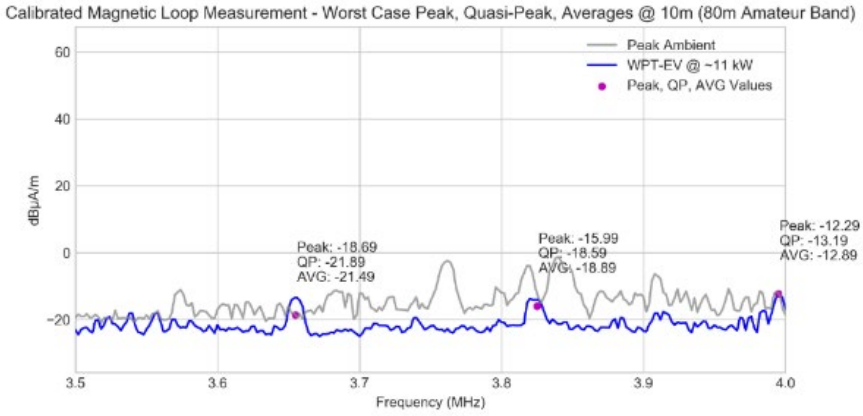


Figure 61: Detailed worst-case calibrated magnetic loop measurements with WPT-EV system on and off for comparison

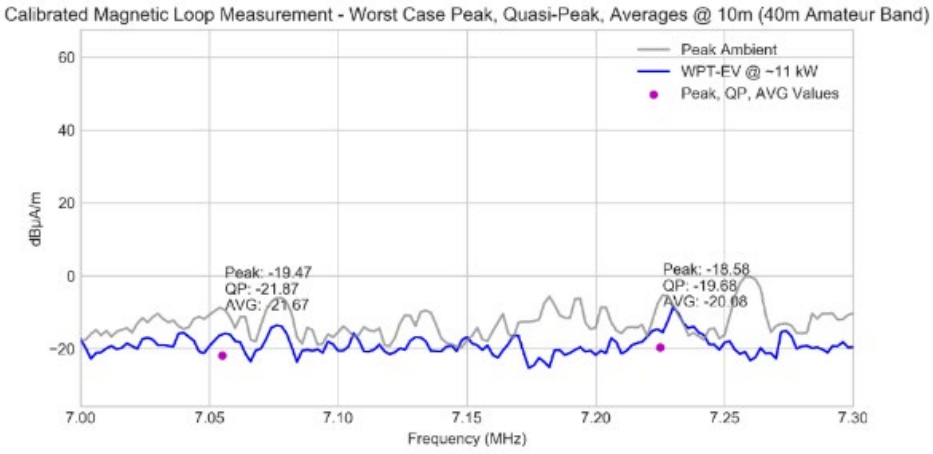


Figure 62: Detailed worst-case calibrated magnetic loop measurements with WPT-EV system on and off for comparison

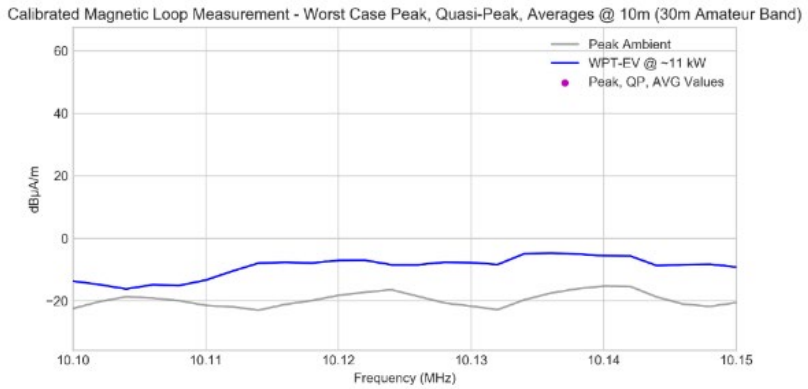


Figure 63: Detailed worst-case calibrated magnetic loop measurements with WPT-EV system on and off for comparison

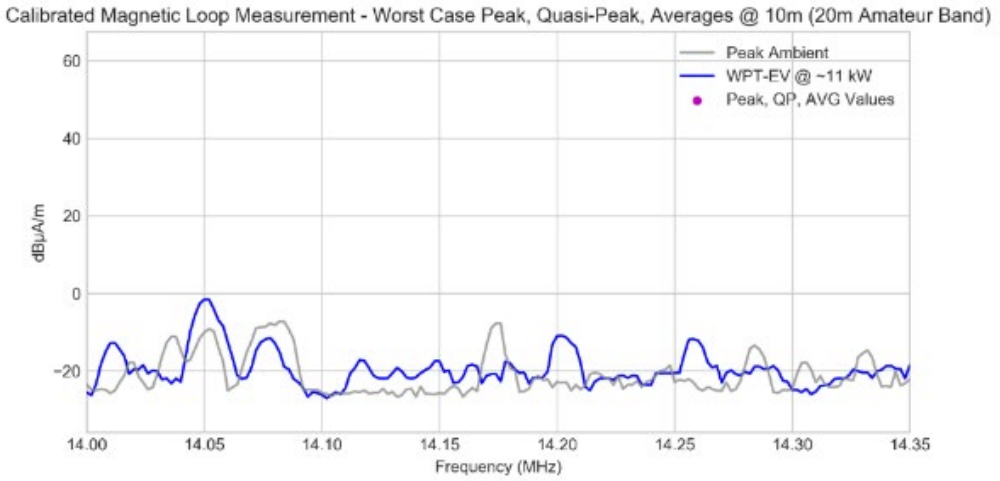


Figure 64: Detailed worst-case calibrated magnetic loop measurements with WPT-EV system on and off for comparison

For brevity, polar plots of the radiation pattern for several of the harmonics are shown below.

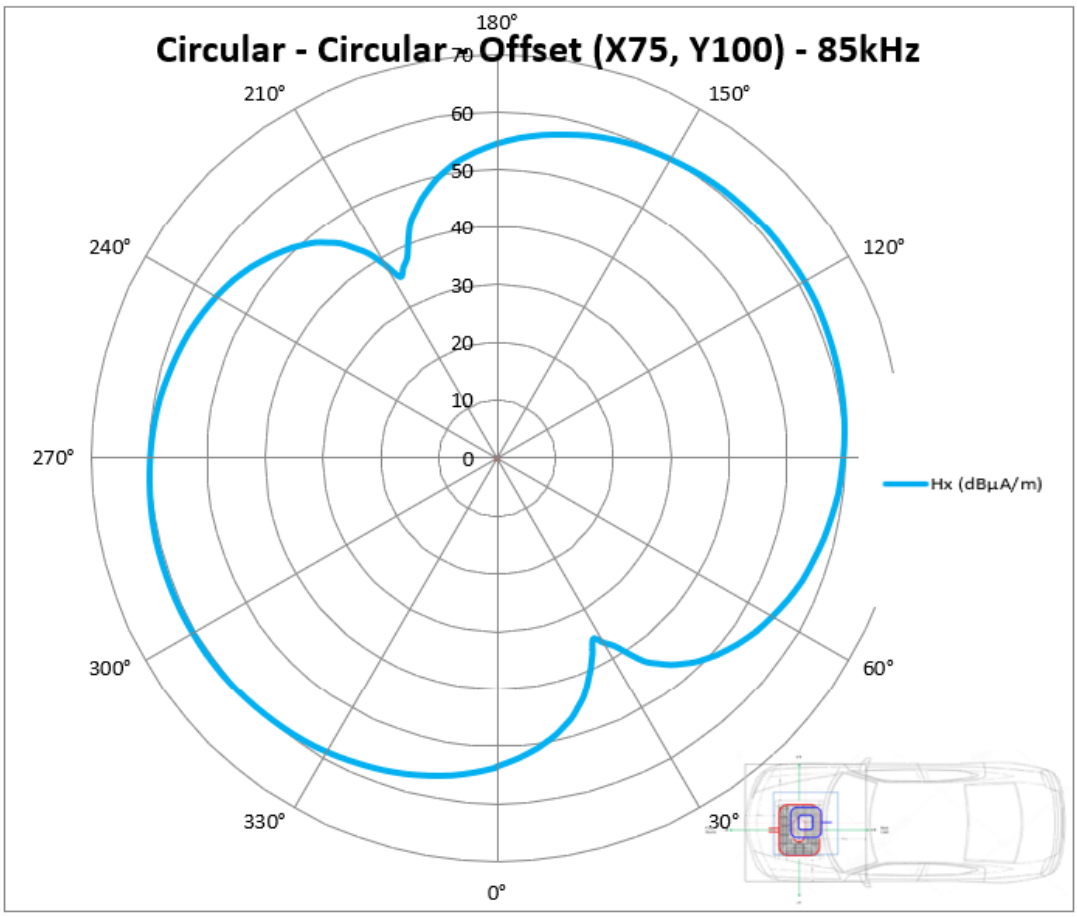


Figure 65: Polar radiation plot for 85 kHz fundamental of WPT-EV system

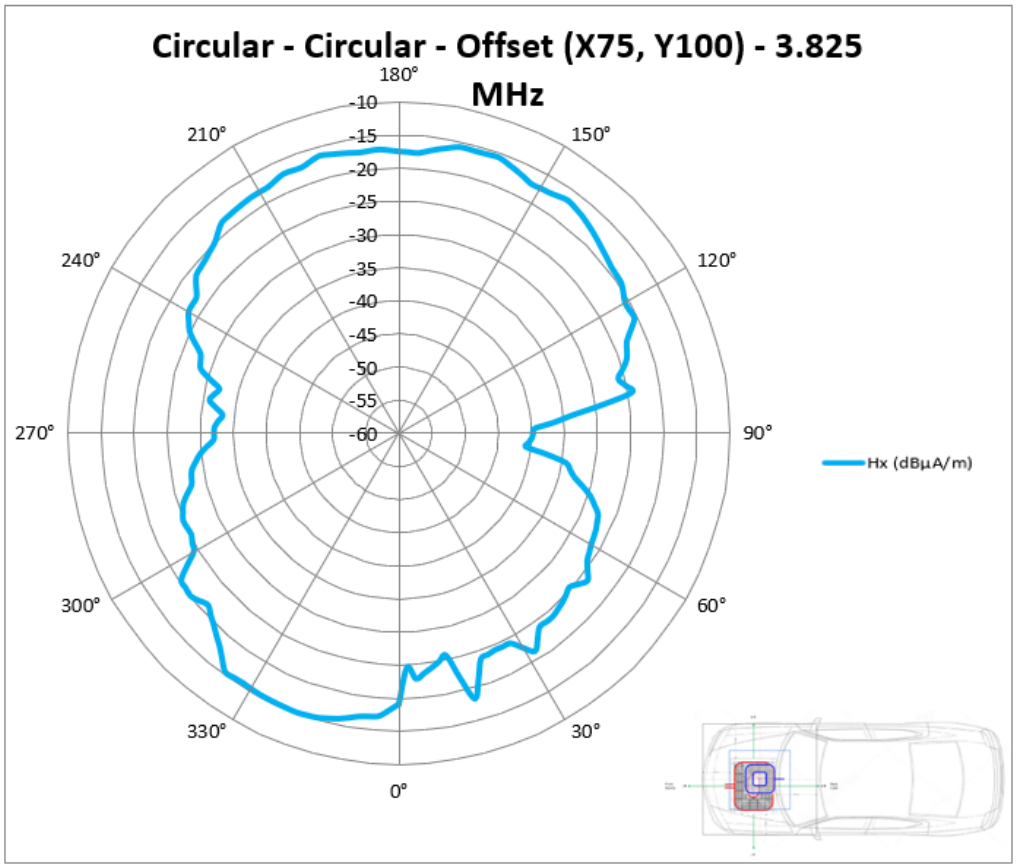


Figure 66: Polar radiation plot for 3.825 MHz harmonic of WPT-EV system

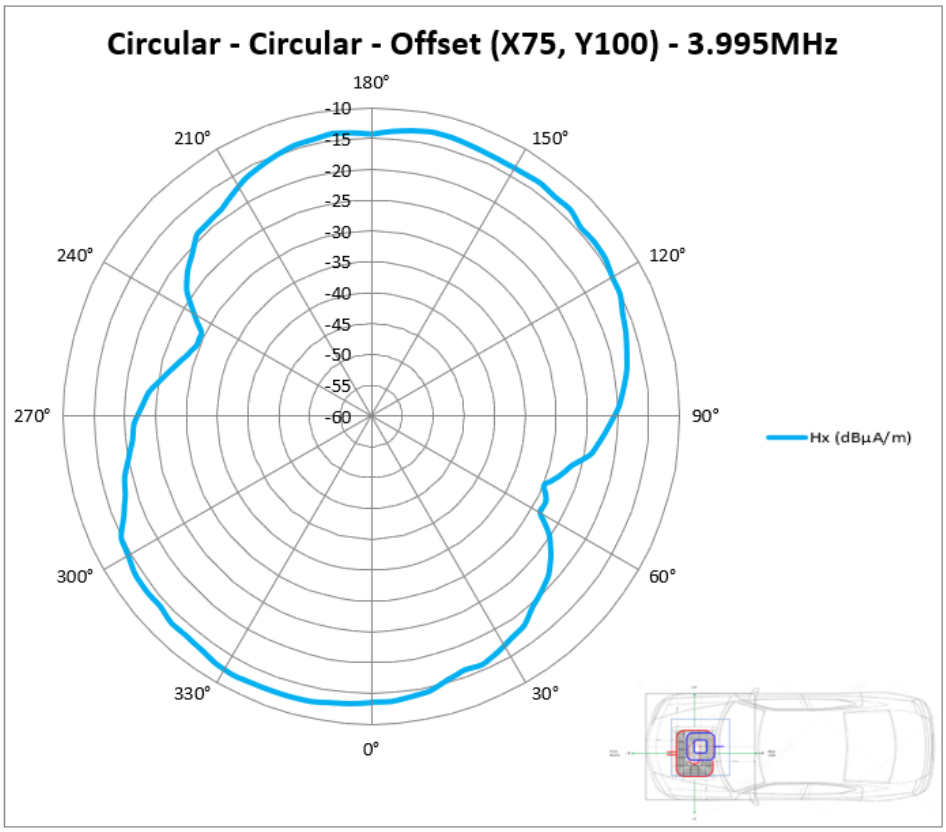


Figure 67: Polar radiation plot for 3.995 MHz harmonic of WPT-EV system

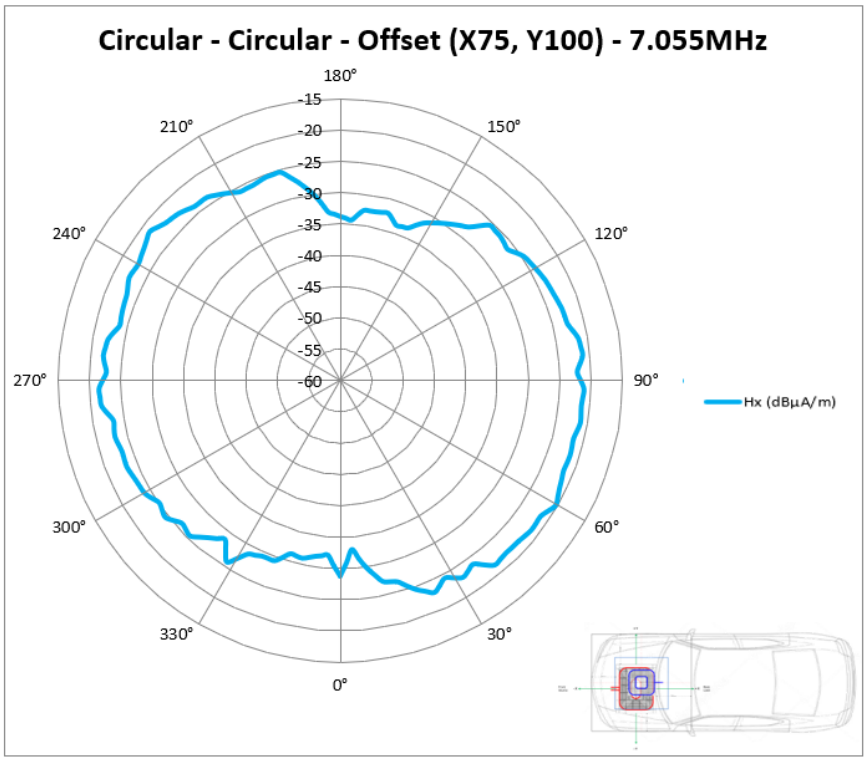


Figure 68: Polar radiation plot for 7.055 MHz harmonic of WPT-EV system

Additionally, to show relative fall-off correlation, several spectrum analyser measurements were collected at 10 m and 3 m distances for comparison. Since the fundamental was a large signal in comparison, attenuators were added and correlation made to ensure that no non-linear or saturation effects were observed due to high signal strength. Table 19 shows the results.

Table 19: Results of spectrum analyser measurements

Frequency	10 m	3 m	3 m 40 dB attenuation	3 m 20 dB attenuation	3 m 10 dB attenuation
85 kHz	41.89 dBµA	62.33 dBµA	22.87 dBµA	42.46 dBµA	52.11 dBµA
1.955 MHz	4.84 dBµA	21.45 dBµA			
3.655 MHz	3.34 dBµA	20.9 dBµA			

Electric field measurements were not made with a monopole antenna. In general, a monopole is more sensitive to vertically polarised noise and responds to surface-wave noise not typically seen by horizontally polarised antennas such as half-wave dipoles commonly used by amateur radio operators [34]. The same characteristics hold true for EMC measurements. The use of narrow-band filtering to improve selectivity, suitable pre-amplifiers for the range of measurement, and an understanding of the ambient environment will all prove useful when performing calibrated measurements using a monopole. Outside the domain of EMC regulatory measurements, radio receivers utilizing a monopole antenna typically require appropriate tuning to improve noise rejection and selectivity in the band of interest. The measurements performed with the amateur radio monopole antenna used for further qualitative testing was supplied with such a matching network for its designated amateur bands of operation (i.e. 80 m to 6 m bands).

Amateur Radio Monopole Antenna Testing

A portable HF amateur radio monopole was chosen based on many qualitative reviews about the antenna from the amateur radio community.,. Due to the large effective height (ratio of induced voltage to incident field) of this chosen antenna compared to smaller antennas typically used for commercial radio broadcasting reception, it was expected and verified that this particular antenna was slightly more sensitive in the HF amateur radio bands. An overview of spectrum from 150 kHz to 15 MHz at 10 m, 20 m and 30 m distances from the WPT-EV system are shown below. The results are based on a max-hold plot with the WPT-EV system rotated slowly on the turn-table to ensure maximum peaks were obtained. The resolution bandwidth was set to 9 kHz. Ambient results with the same antenna configuration were collected separately with the WPT-EV system OFF for comparison with the WPT-EV system ON.

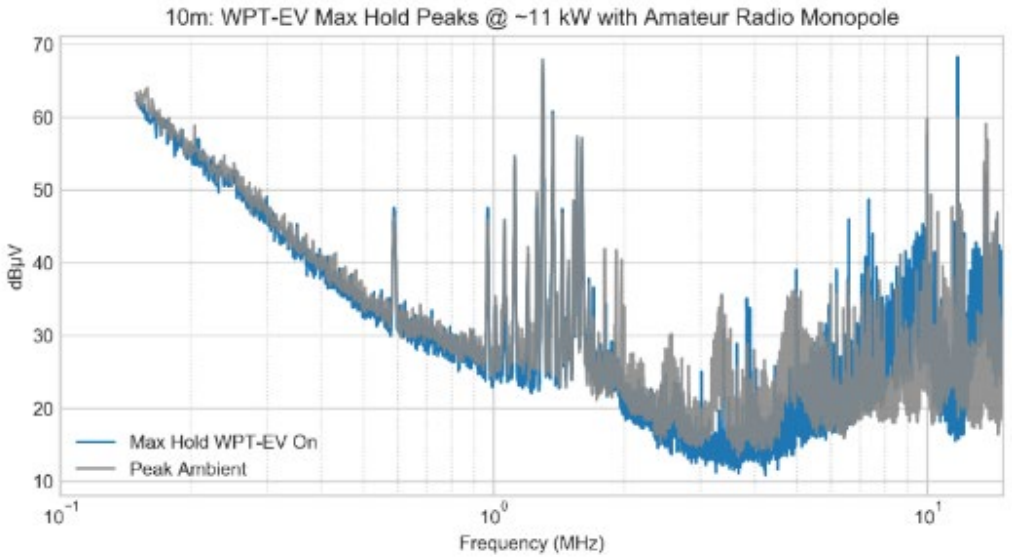


Figure 69: Peak measurements at a distance of 10 m using amateur radio monopole with WPT-EV system on and off for comparison

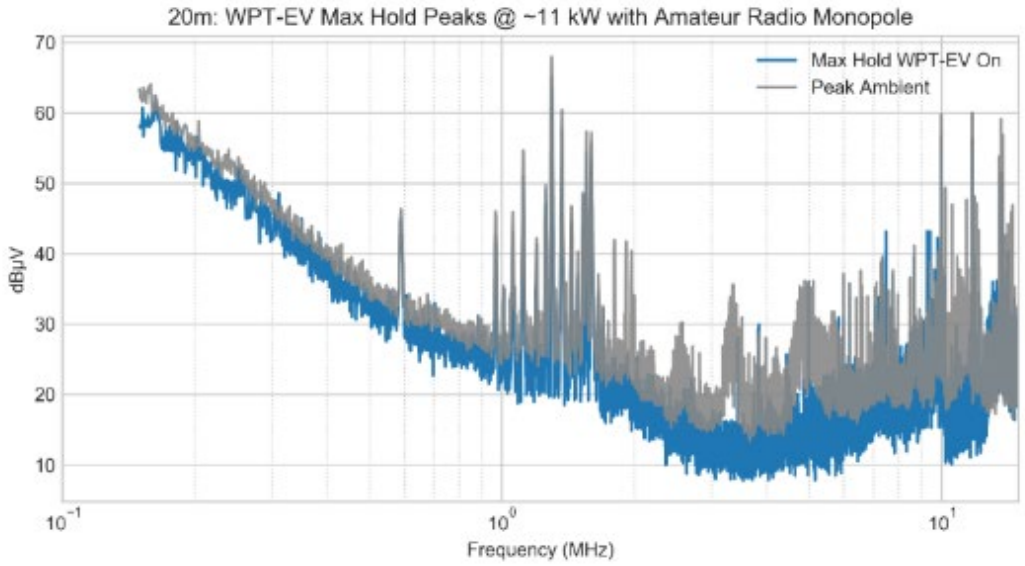


Figure 70: Peak measurements at a distance of 20 m using amateur radio monopole with WPT-EV system on and off for comparison

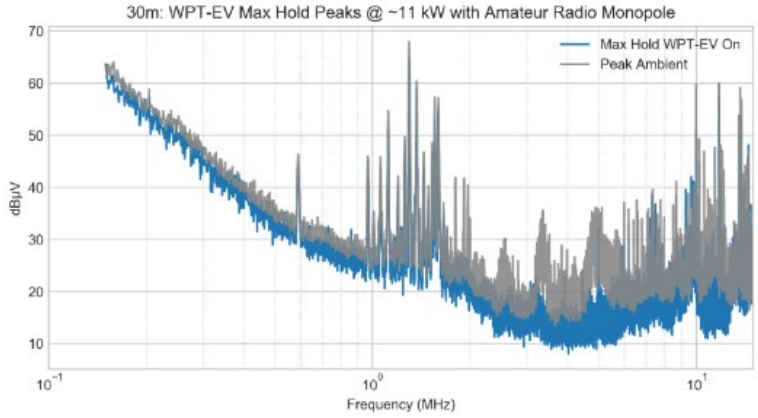


Figure 71: Peak measurements at a distance of 30 m using amateur radio monopole with WPT-EV system on and off for comparison

For better qualitative comparison, plots in each of the 80 m, 40 m, 30 m and 20 m amateur radio bands are shown taken at distances of 10 m, 20 m and 30 m from the WPT-EV system. The 80 m amateur band at the various distances is shown below along with the marked expected locations of the WPT-EV odd harmonics.

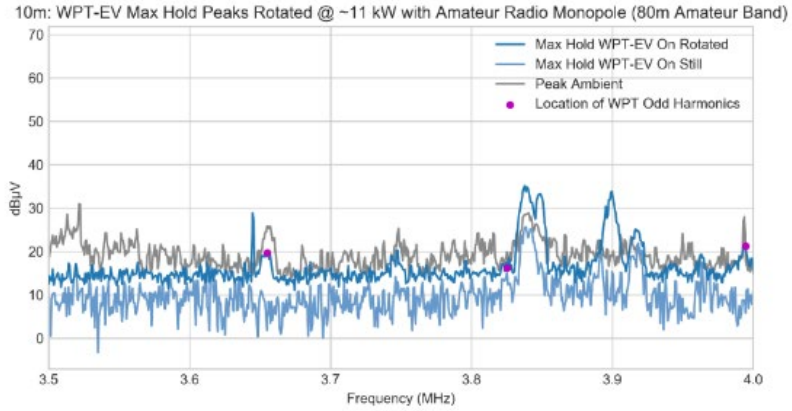


Figure 72: Peak measurements at a distance of 10 m using amateur radio monopole with WPT-EV system on and off for comparison

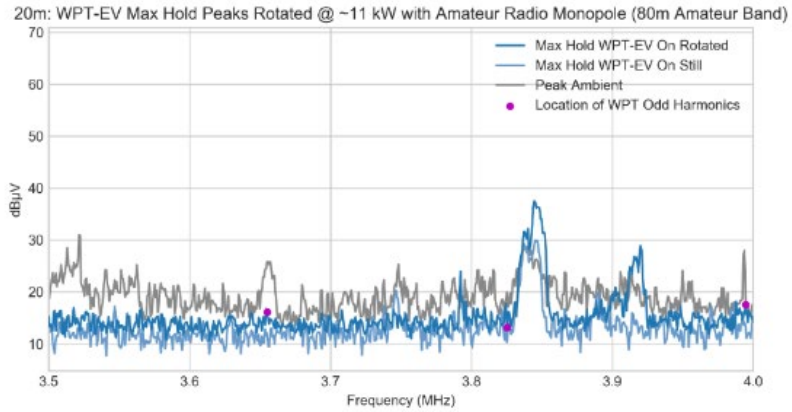


Figure 73: Peak measurements at a distance of 20 m using amateur radio monopole with WPT-EV system on and off for comparison

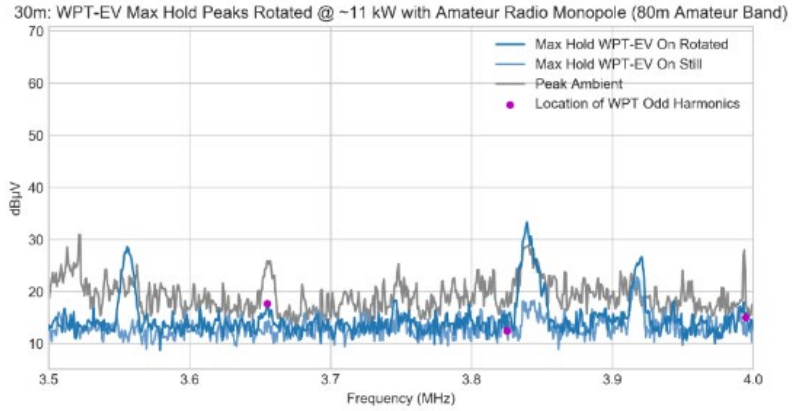


Figure 74: Peak measurements at a distance of 30 m using amateur radio monopole with WPT-EV system on and off for comparison

The 40 m amateur band at the various distances is shown below.

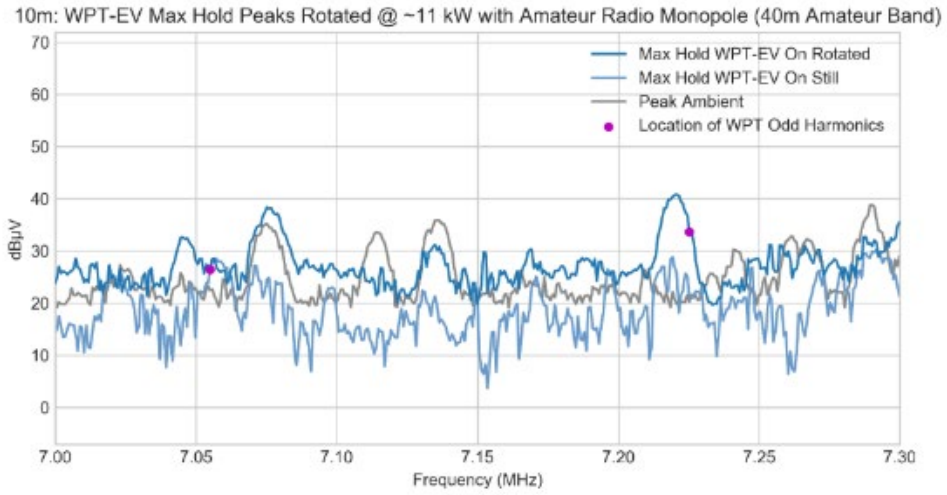


Figure 75: Peak measurements at a distance of 10 m using amateur radio monopole with WPT-EV system on and off for comparison

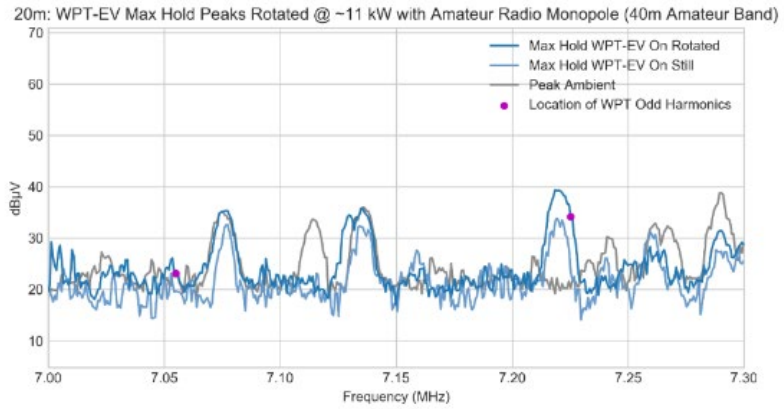


Figure 76: Peak measurements at a distance of 20 m using amateur radio monopole with WPT-EV system on and off for comparison

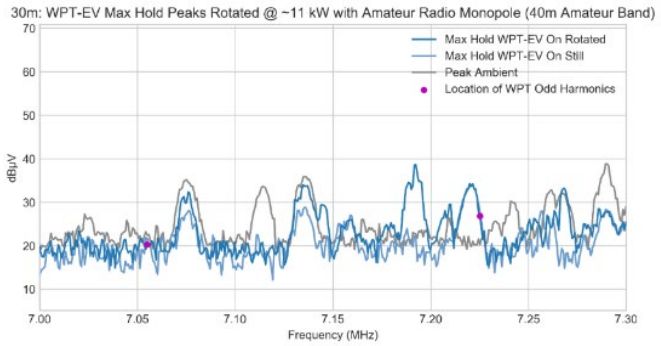


Figure 77: Peak measurements at a distance of 30 m using amateur radio monopole with WPT-EV system on and off for comparison

The plots for the 30 m amateur band at the various distances are shown below.

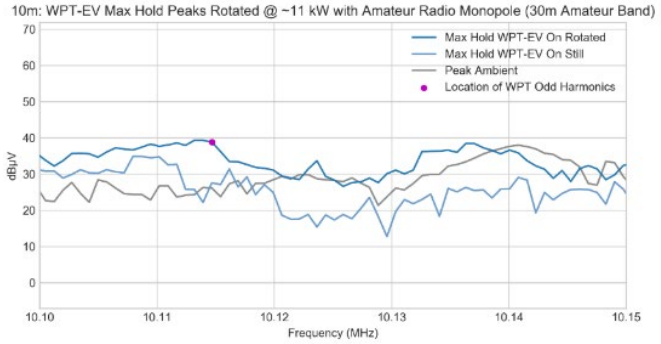


Figure 78: Peak measurements at a distance of 10 m using amateur radio monopole with WPT-EV system on and off for comparison

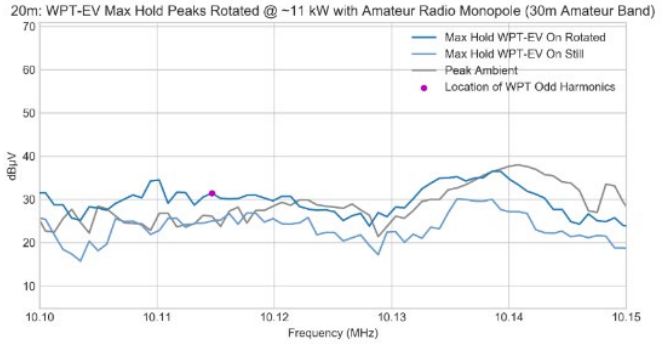


Figure 79: Peak measurements at a distance of 20 m using amateur radio monopole with WPT-EV system on and off for comparison

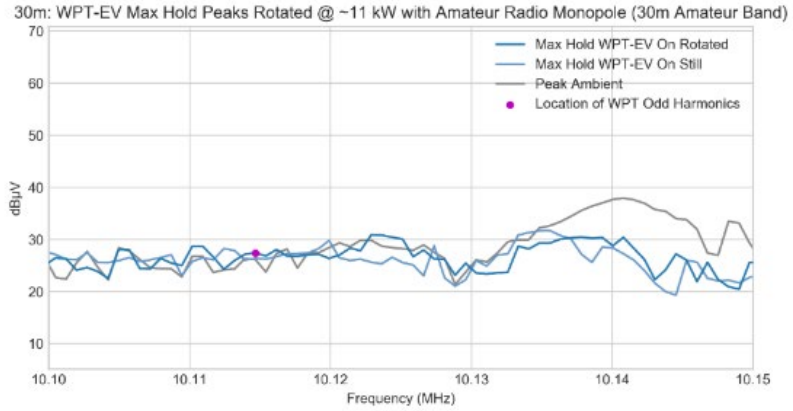


Figure 80: Peak measurements at a distance of 30 m using amateur radio monopole with WPT-EV system on and off for comparison

The plots for the 20 m amateur band at the various distances are shown below.

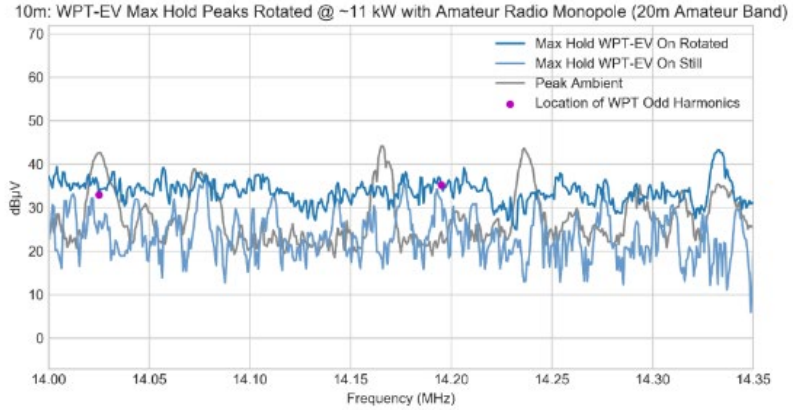


Figure 81: Peak measurements at a distance of 10 m using amateur radio monopole with WPT-EV system on and off for comparison

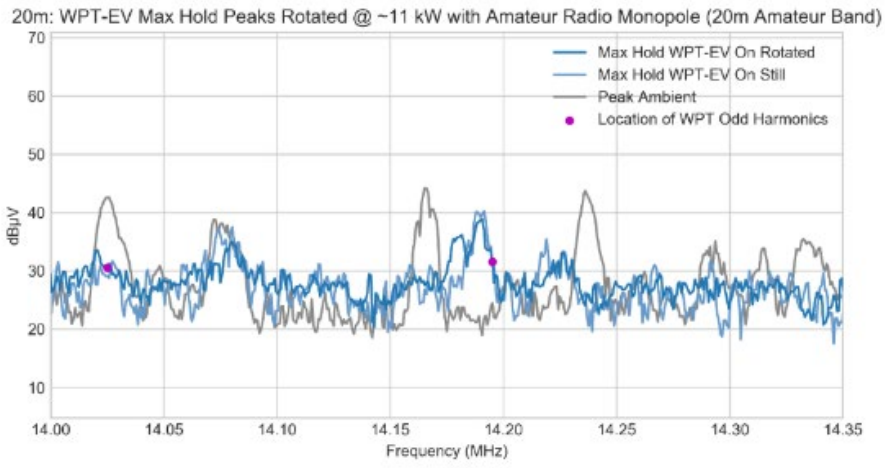


Figure 82: Peak measurements at a distance of 20 m using amateur radio monopole with WPT-EV system on and off for comparison

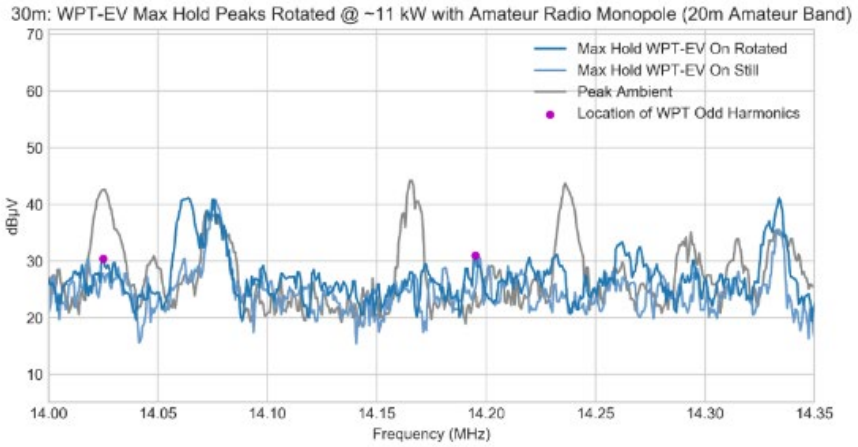


Figure 83: Peak measurements at a distance of 30 m using amateur radio monopole with WPT-EV system on and off for comparison

In addition to the various plots collected from the calibrated spectrum analyser, the amateur radio transceiver and receiver were used to assess qualitative audio impact of the WPT-EV system on communications. In general, at the various distances, no visual or audio impact in the tested amateur radio bands (80 m, 40 m, 30 m, 20 m) was detected above the ambient environment levels present at this site whenever the vehicle was reasonably aligned and rotated on the turn table. However, in one specific worst-case condition where the ground assembly coil and vehicle assembly coil were misaligned to maximum offset, the turn table was set to a specific angle relative to the amateur monopole antenna, and the antenna had an NVIS line attached to increase near-field sensitivity at a distance of 10 m from the WPT-EV system, audio characteristics from the WPT-EV were detectable as a faint “whistle”. In this same condition, a faint SSB voice transmission was also recorded directly over top of the interference signal at 3.825 MHz.

Despite the faintly heard WPT-EV interference, this voice transmission was clearly audible and intelligible. A before and after image of the recorded transmission using the Airspy HF+ Discovery receiver and SDRSharp radio software are shown below along with an overlay.

The interference signal from the WPT-EV system at 3.825 MHz using the SDRSharp software is shown below.

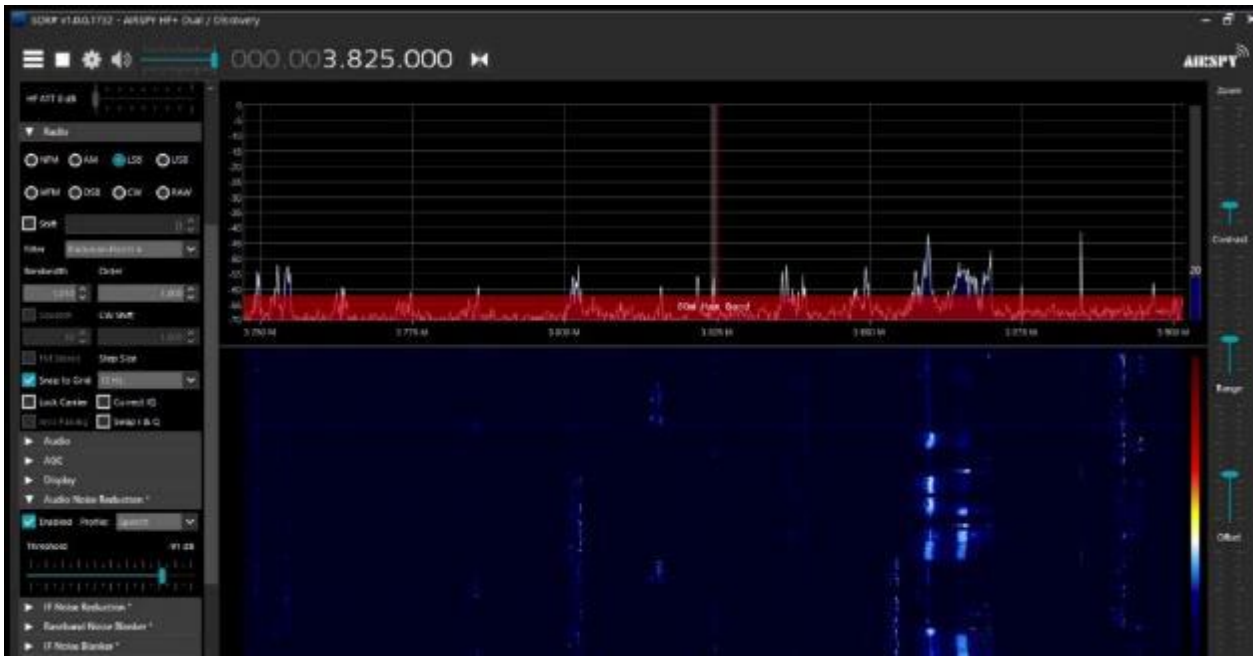


Figure 84: Snapshot of WPT-EV interference signal at 3.825 MHz in worst-case condition

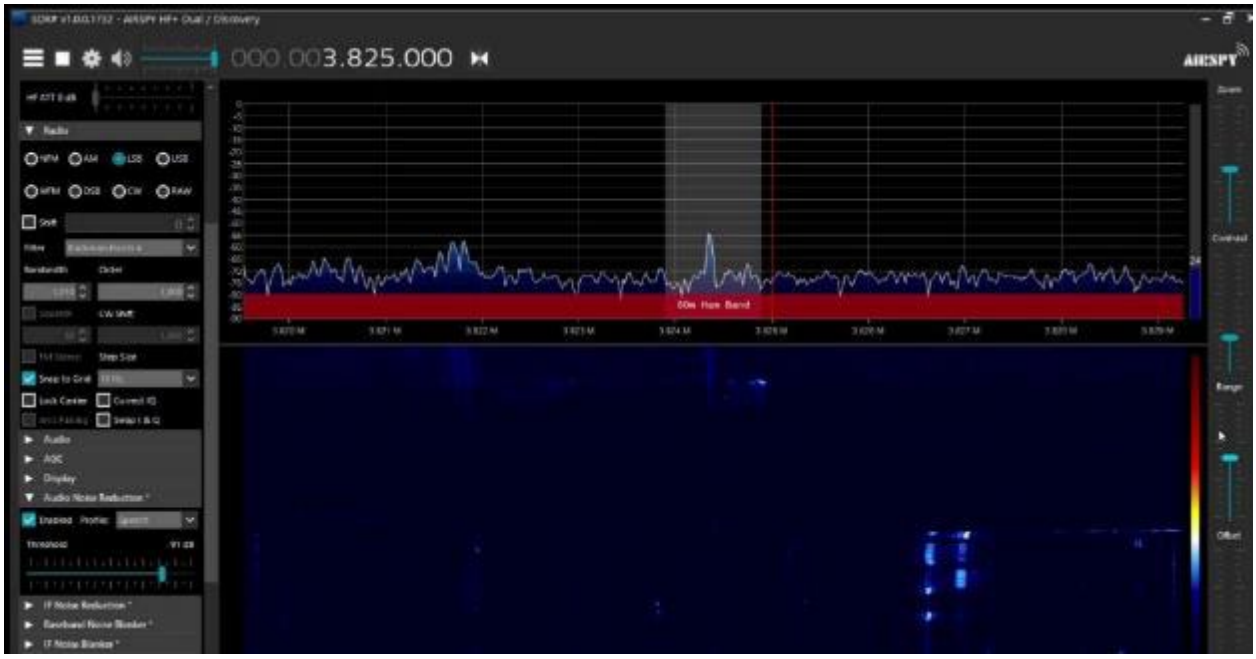


Figure 85: Zoomed snapshot of WPT-EV interference signal at 3.825 MHz in worst-case condition

A distant amateur radio voice transmission occurred at the same frequency as the WPT-EV harmonic interference captured and is shown below.

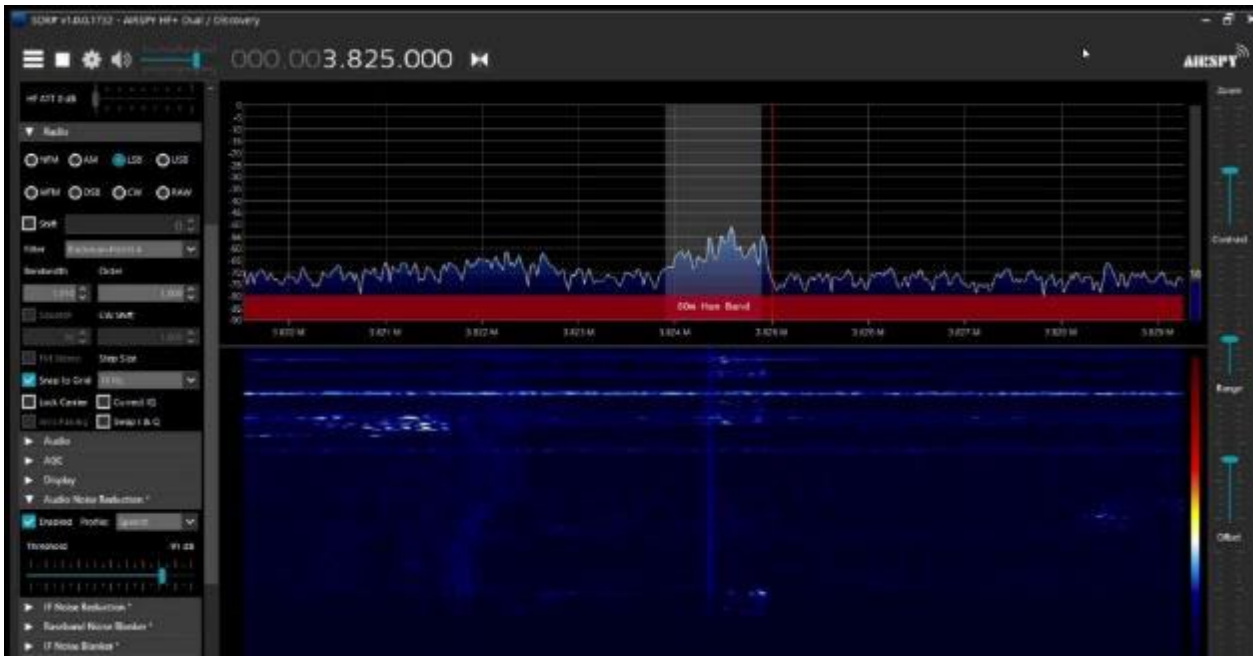


Figure 86: Zoomed snapshot of distant amateur radio verbal audio broadcast at 3.825 MHz with interferer present

An overlay of the interference and the SSB AM transmission together and shown below.

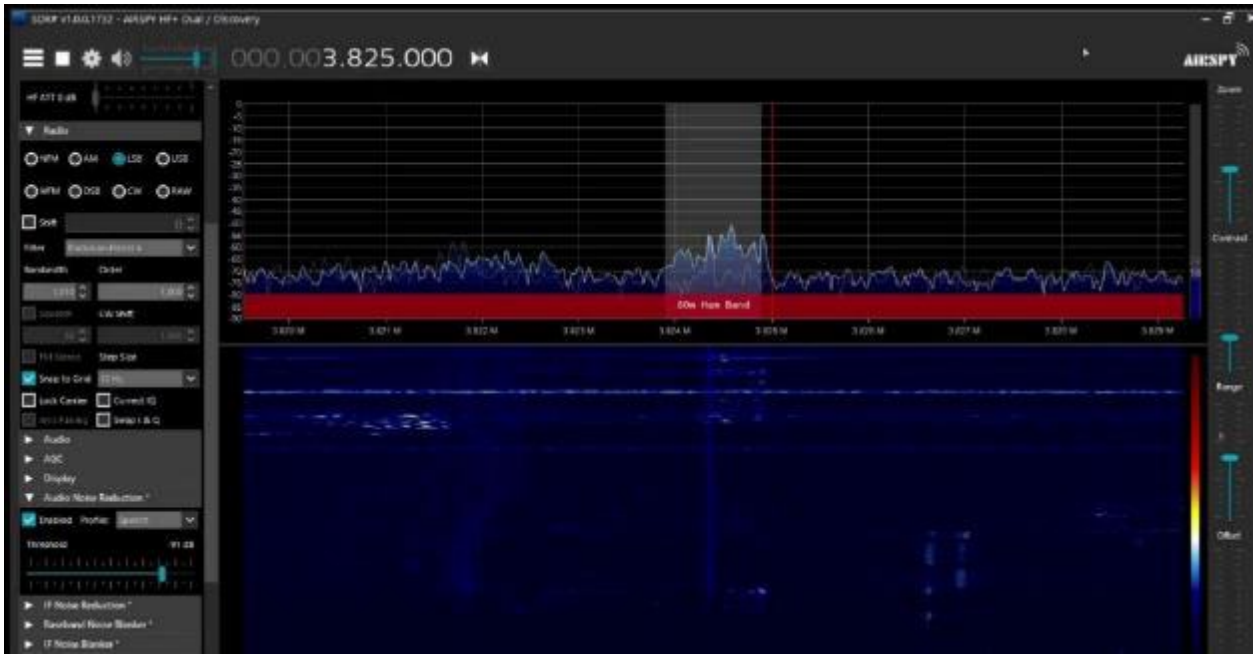


Figure 87: Zoomed snapshot of distant amateur radio verbal audio broadcast at 3.825 MHz with WPT-EV interference signal underlay

Following the qualitative testing, additional characterisation of the amateur radio monopole and the SDR were performed to convert the signal strengths from the levels shown in the software to vertically polarised electric-field levels. The result of this conversion is shown in the below figure. Note: Care should be exercised when viewing the noise trace in these figures because of limitations in some SDRs.

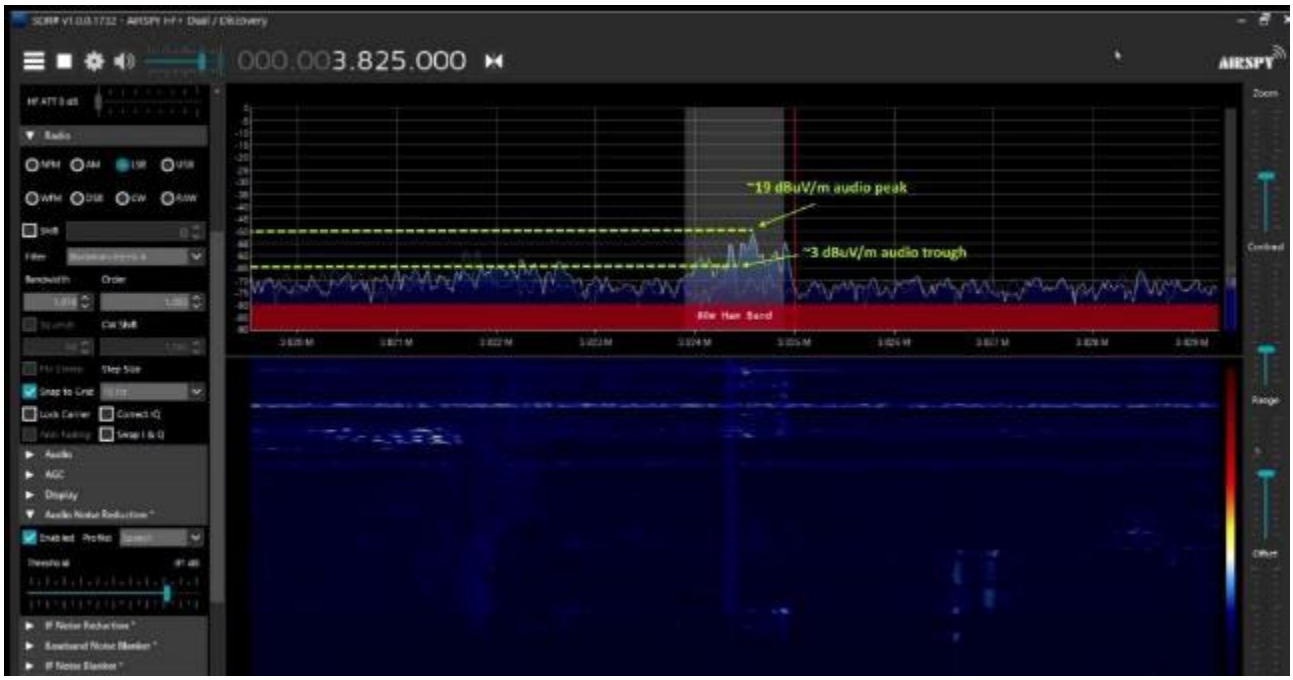


Figure 88: Zoomed snapshot of distant amateur radio verbal audio broadcast at 3.825 MHz with WPT-EV interference signal underlay and E-Field levels (note that the field values are estimations based on the SDR levels and therefore have margins of error)

A1.5 SUMMARY OF RESULTS

A WPT-EV system as defined by the referenced SDOs operating at ~11 kW input power and ~90% efficiency AC grid input to DC battery output mounted on an EV with a 62 kWh battery was measured on a third-party accredited Open Area Test Site (OATS). The characteristics of the ambient environment were collected for comparison of emissions with the WPT-EV system transferring power and turned off. Ambient characteristics measured using an HF amateur radio monopole antenna recommended by radio amateurs for the designated operating bands were collected at the OATS and compared directly with the same measurement performed in a rural area separated by ~1300 miles or ~2100 km. In the 80 m and 40 m bands, the ambient measurements showed similar characteristics, whereas in the 30 m and 20 m bands, the levels in Nibley, Utah were typically up to ~10 dB lower than those in Cedar Park, Texas. Other ambient environment comparisons were also made with other measurement campaigns, e.g. one in Ersigen, Switzerland, as given in Annex 2 of this Addendum. These additional comparisons indicate that the ambient conditions of the study are at least similar to another residential location in a different part of the world. The ambient environment comparison, however, can be applied to other locations and amateur installations only if the environment and ambient conditions are similar to what they are in the specific locations measured. Additionally, these measurements were made using EMC measurement techniques, so they do not represent the median man-made noise (MMN) values indicated in Recommendation ITU-R P.372 [25].

The WPT-EV system was setup to operate continuously at full-power transfer and in worst-case misaligned conditions. Radiated emission data in the 9 kHz to 30 MHz range was collected by a third-part accredited laboratory using calibrated equipment used to perform certification measurements required by local administrations. Measurements were performed with a standard calibrated CISPR 60 cm loop antenna at a distance of 10 m. The magnetic loop antenna showed the WPT-EV operating fundamental as well as some other emissions above the ambient conditions present at the OATS. Detailed quasi-peak and average measurements were also taken with the magnetic loop antenna on discernible WPT-EV odd harmonics seen above ambient conditions in the 80 m to 20 m amateur radio bands. Radiation patterns were obtained for the fundamental as well as the measured harmonics.

For direct comparison and correlation with the calibrated measurements taken, additional data was collected by licensed amateur radio operators using a monopole antenna with a large effective antenna height. The amateur radio antenna was placed at distances of 10 m, 20 m and 30 m over real earth from the WPT-EV system that was located on the OATS (and rotated for maximum interference potential). In several unique cases, very narrow-band harmonics were discernible with the amateur radio monopole antenna but although their amplitude was no higher than the typical ambient peaks seen without the WPT-EV system operating.

Qualitative listening tests were also conducted in the presence of WPT emissions. One amateur service signal operating in the far-field with an average E-Field strength of ~16 dBµV/m (~-35 dBµA/m) was heard at a frequency coinciding with a WPT harmonic and resulted in an intelligible and audible voice transmission yielding non-harmful interference. In this case, the approximate amateur signal-to-ambient-noise-peak ratio was about 13 dB with the ambient noise peaks occurring at an average of ~-2 dBµV/m (~-53.5 dBµA/m). (It should be noted that the amateur signal level values are estimated based on uncalibrated SDR measurements and thus have a margin of error in the estimation. In the near-field, where the WPT-EV system is located at a 10 m distance, the calibrated H-Field EMC measurements cannot be converted to E-Field using far-field approximations. Further work is encouraged to examine the full impact of the measured levels of WPT emissions on general communications in the amateur service in multiple environments.

ANNEX 2: INTERFERENCE TRIALS IN SWITZERLAND BETWEEN WPT-EV INDUCTIVE CHARGING AND AMATEUR RADIO

A2.1 EXECUTIVE SUMMARY

An empirical investigation is documented in this study which shows that a properly designed inductive charging system for electric vehicles (WPT) does not disturb amateur radio communication in a residential environment.

The investigation was done with a 3.7 kW series-production WPT system and measured with one car charging.

The investigation has been carried out by field trials in August and September 2020 in Ersigen, Switzerland.

A2.2 INTRODUCTION

There is only a limited number of publicly available reports on EMC measurements available to help the different stakeholders to evaluate the EMC risks of WPT systems.

Measurements were conducted on a single car charging system[5]. This system is optimised regarding EMC in the frequency range above 1 MHz.

A2.3 MEASUREMENT SETUP

The vehicle was parked in two locations. One in 30 m (location 1) distance from the amateur station, the other one in 10 m (location 2) distance.

H-Field Measurement @ 10 m distance (Active Loop-Antenna)

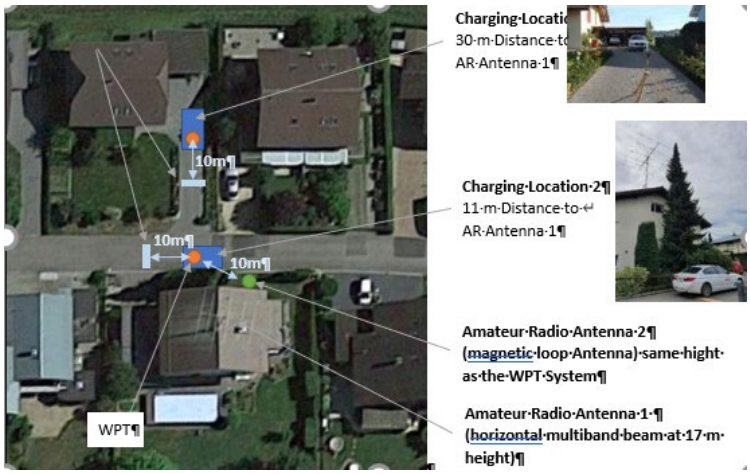


Figure 89: Measurement Situation

The measurements took place on 25.08.2020 and 23.09.2020 at Lindenmattweg 15, Ersigen, Switzerland. The location can be categorised as residential and the used radio equipment is a typical amateur radio station.

[5] The WPT system is the ICS1 system integrated in a BMW 530e and manufactured by BRUSA Elektronik AG.



Figure 90: Measurement Location

A2.3.1 Magnetic Field Strength Measurement

Magnetic field strength measurements were conducted using an active loop antenna. The measurement receiver was put into Realtime-Modus (Scan) to enable continuous and fast measurement of Quasi Peak values over the full frequency range. Measuring equipment and parameters are compliant to CISPR requirements for magnetic field measurements in the frequency range 9 kHz to 30 MHz.

A2.3.1.1 Antenna orientations X, Y and Z

X, parallel Y, vertical Z, horizontal to front of vehicle; D = Distance 10 m

The Antenna was a standard 60 cm Loop antenna (H-Field). The antenna centre was placed 1.3 m above ground.

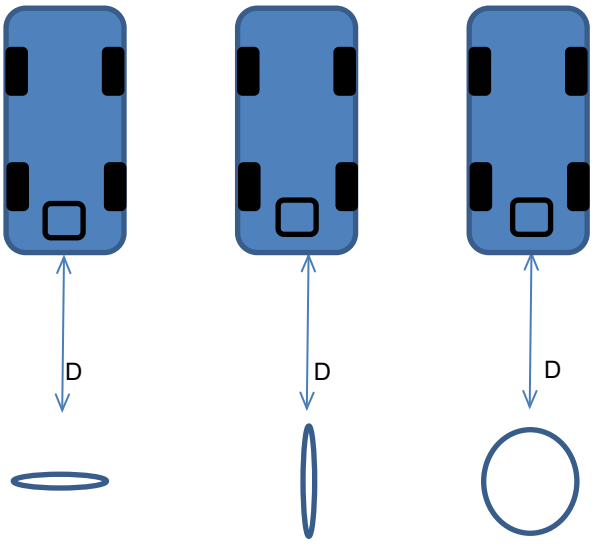


Figure 91: Antenna orientations

A2.3.1.2 Equipment



Figure 92: Active Loop Antenna



Figure 93: Receiver



Figure 94: Filter for Measurement above 150 kHz



Figure 95: Measurement Vehicle

A2.4 IMPACT ON RADIO AMATEUR SERVICE

A2.4.1 Amateur Radio Antenna 1

The impact on amateur radio service was measured on a typical amateur radio system operated with a horizontal polarised Yagi antenna. This amateur radio station is equipped for the reception of signals at the HF-frequencies 21 MHz, 28 MHz and 14 MHz. The horizontal Yagi beam antenna is at a height of 17 m above ground, as shown in Figure 94 and was rotated to have the main beam pointing towards the WPT system under test.

To investigate the impact of the WPT system, an IC7600 transceiver and a FPC1000 spectrum analyzer were used to measure the HF signal power from amateur radio antenna 1.



Height: 17 m
Type: Yagi: Fritzel-Beam FB660 DX
Antenna factor (incl. Losses to RX-Input)
f = 14.2 MHz: 3 El., AFe -13.5 dB/m
f = 21.2 MHz: 5 El., AFe -11.5 dB/m
f = 28.4 MHz: 5 El., AFe -9 dB/m
f = 7.1 MHz: Inv. V, AFe -13 dB/m
f = 3.7 Mhz: Inv. V, AFe -18.5 dB/m
Details: HBradio 4/2017, p. 11
(in German)

Figure 96: Amateur Radio Antenna 1 used for the tests

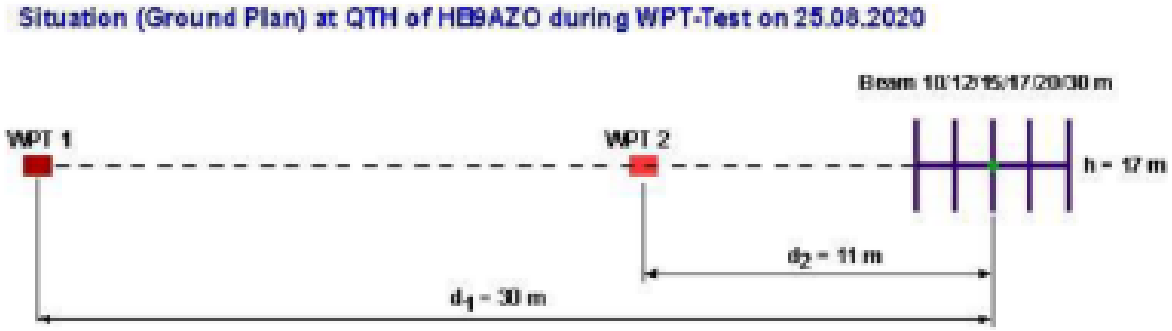


Figure 97: Ground Plan of Test Situation at QTH of HB9AZO

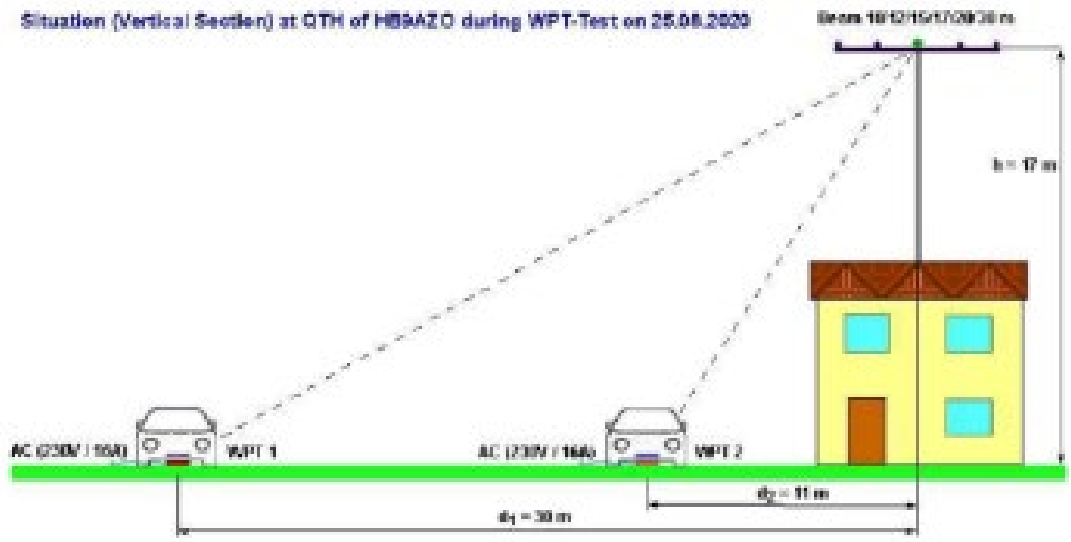


Figure 98: Vertical Section of Test Situation at QTH of HB9AZO

A2.4.1.1 Amateur Radio Antenna 2



Figure 99: Situation Measurement Radio Antenna 2



Figure 100: Radio Antenna 2 (MegaLoop FX)



Figure 101: Situation Measurement Radio Antenna 2



Figure 102: Receiver for Antenna 2 (ICOM IC-705)

Because the main beam of the Yagi antenna was not pointing to, but above the WPT system, the Yagi antenna would be operated out of specifications when used as measurement antenna for this test set up. Therefore, in a second measurement setup, operated by an electrically small active magnetic loop antenna, placed above ground, was used to measure magnetic fields. The antenna loop wire has a circumference of 2 m ($\phi \sim 60$ cm). Preamp 2 of IC-705 was switched on for all shortwave bands from 1.8 MHz to 28 MHz, and the gain setting for the waterfall display was at +15 dB. The MegaLoop FX internal amplifier gain was set to medium position (20 dB gain). The noise blanker in the IC-705 was set to on, to remove interference from the nearby farmer's electric fence. This had no impact on the signal to be analysed, as the WPT-EV charging is continuous. All equipment for antenna setup 2 was powered from batteries.

The antenna factor of this antenna 2 is unknown. With this setup, it was possible to receive e.g. stations in Indonesia (YB) on 21 MHz with a signal-to-noise ratio that was only slightly lower than on antenna 1 (the beam). While this antenna is not suitable for transmitting, it is certainly an adequate solution for receiving.

A2.4.2 WP-EV charger input Power Measurement

The WPT-EV input power was measured with a Camille Bauer Metrawatt AG AM1000. The input current, voltage and power were logged with a laptop each 10 s.



Figure 103: Input Power Measurement

In order to eliminate a possible influence of conducted and/or radiated disturbances from the power supply cable of the WPT, the cable was connected to a power outlet of 230 V / 16 A on the other side of the street. In addition, the cable was placed in a CMAD (common mode absorbing device) close to the WPT.

A2.4.3 WPT System

The WPT system is an ICS1 3,7 kW system of BRUSA Elektronik AG integrated in a BMW 530e. The ground assembly sample is taken from a series production lot. The system (vehicle, ground assembly, vehicle assembly) were randomly chosen without selecting a specifically optimal sample. The system was produced in 2018.



Figure 104: Vehicle ground assembly



Figure 105: BRUSA ICS1 WPT System

The used ICS1 system is an integrated system with fully functioning ground and vehicle assemblies. During the test, all functions were operating with production software (SW) and without derating. The functions were:

- Power transfer;
- WAS/RLAN communication;
- Metal detection (FOD);
- Living object detection (LOD);
- Positioning system;
- Safety functions.

The system has certification from TÜV Rheinland for Japan, China, Europe, North America.

Model / Type: ICSP11W-U0-01D-K01 (GPM); ICSS115-U0-01D-L01 (CPM)

Most measurements in this test series were performed with an AC input power of 3.7 kW (see XX). Before starting the measurements, it was ensured that the rechargeable battery in the vehicle was sufficiently discharged in order to allow charging during the entire test time.

A2.5 MEASUREMENT RESULTS

A2.5.1 Input Power

Time was split in different timeslots with a specific ID in order to synchronize the different measurements.

Table 20: ID-Numbers used for indication of Input Current (proportional to power), time and WPT operation state (OFF and ON)

Timeslot ID	I1 [Aeff]	Start Time	Stop Time	Date	WPT state	Distance Vehicle – Antenna 1 center
ID0	0	00:00:00	09:00:00	25.08.2020	WPT OFF	30 m
ID1	0	08:54:30	09:25:30	25.08.2020	WPT OFF	30 m
ID2	11.3	08:59:00	09:03:20	25.08.2020	Charging	30 m
ID3	0	09:03:30	09:10:10	25.08.2020	WPT OFF	30 m
ID4	11.3	09:10:30	09:26:40	25.08.2020	Charging	30 m
ID5	0	09:26:50	09:39:20	25.08.2020	WPT OFF	30 m
ID6	11.3	09:39:40	09:41:30	25.08.2020	Charging	30 m
ID7	0	09:41:40	09:42:40	25.08.2020	WPT OFF	30 m
ID8	11.3	09:43:00	09:51:30	25.08.2020	WPT ON	30 m
ID9	0	09:51:40	10:42:00	25.08.2020	WPT OFF	30 m
ID10	11.3	10:42:30	11:07:20	25.08.2020	WPT ON	30 m
ID11	0	11:07:30	11:33:10	25.08.2020	WPT OFF	30 m
ID12	11.3	11:33:30	11:51:50	25.08.2020	WPT ON	30 m
ID13	0	11:52:00	11:53:30	25.08.2020	WPT OFF	30 m
ID14	0	13:32:30	13:33:00	25.08.2020	WPT OFF	30 m

Timeslot ID	I1 [Aeff]	Start Time	Stop Time	Date	WPT state	Distance Vehicle – Antenna 1 center
ID15	11.3	13:33:20	13:39:20	25.08.2020	WPT ON	11 m
ID16	16.1	13:39:40	13:51:00	25.08.2020	WPT ON MAX	11 m
ID17	0	13:51:20	14:05:50	25.08.2020	WPT OFF	11 m
ID18	16.1	14:06:20	14:19:30	25.08.2020	WPT ON MAX	11 m
ID19	0	14:19:50	14:22:10	25.08.2020	WPT OFF	11 m
ID20	16.1	14:22:40	14:52:50	25.08.2020	WPT ON MAX	11 m
ID21	0	14:53:10	15:04:10	25.08.2020	WPT OFF	11 m
ID22	16.1	15:04:40	15:05:10	25.08.2020	WPT ON MAX	11 m
ID23	0	15:05:30	15:06:00	25.08.2020	WPT OFF	11 m
ID24	16.1	15:06:40	15:06:40	25.08.2020	WPT ON MAX	11 m
ID25	0	15:07:00	24:00:00	25.08.2020	WPT OFF	11 m
ID26	0	0:00	9:37	23.09.2020	WPT OFF	11 m
ID27	16.1	9:37	9:39	23.09.2020	WPT ON MAX	11 m
ID28	0	9:39	9:45	23.09.2020	WPT OFF	11 m
ID29	16.1	9:45	9:55	23.09.2020	WPT ON MAX	11 m
ID30	0	9:55	10:00	23.09.2020	WPT OFF	11 m
ID31	16.1	10:00	10:10	23.09.2020	WPT ON MAX	11 m
ID32	0	10:10	10:15	23.09.2020	WPT OFF	11 m
ID33	16.1	10:15	10:25	23.09.2020	WPT ON MAX	11 m
ID34	0	10:25	11:15	23.09.2020	WPT OFF	11 m
ID35	16.1	11:15	11:25	23.09.2020	WPT ON MAX	11 m
ID36	0	11:25	11:30	23.09.2020	WPT OFF	11 m
ID37	16.1	11:30	11:40	23.09.2020	WPT ON MAX	11 m
ID38	0	11:40	11:45	23.09.2020	WPT OFF	11 m
ID39	16.1	11:45	11:55	23.09.2020	WPT ON MAX	11 m
ID40	0	11:55	12:00	23.09.2020	WPT OFF	11 m
ID41	16.1	12:00	13:00	23.09.2020	WPT ON MAX	11 m

A2.5.2 Magnetic Field Strength Measurement

A2.5.2.1 General Consideration on the Measurements and the Results

The measurements were done with peak detector (Pk) and quasi peak (QP) detector in real time mode. The frequency band from 9 kHz to 30 MHz is covered by two separate measurements, the first one from 9 kHz to

150 kHz with a bandwidth of 200 Hz and the second, above 150 kHz, with 9 kHz bandwidth. Three traces were recorded for each measurement (example below in Figure 106), trace 1 (purple) is the actual Pk measurement (clear write, Clrw), trace 2 (green) is the actual QP measurement (clwr) and trace 3 (orange) is the max hold of Pk measurement. The limits shown in the plot are limits for class B WPT from IEC 61980-1 [8] and the measurements done during this campaign are not intended to assess the conformity of the WPT but only to collect information about emission of a WPT system actually available on the market. The limit shown in the plot shall only provide a reference.

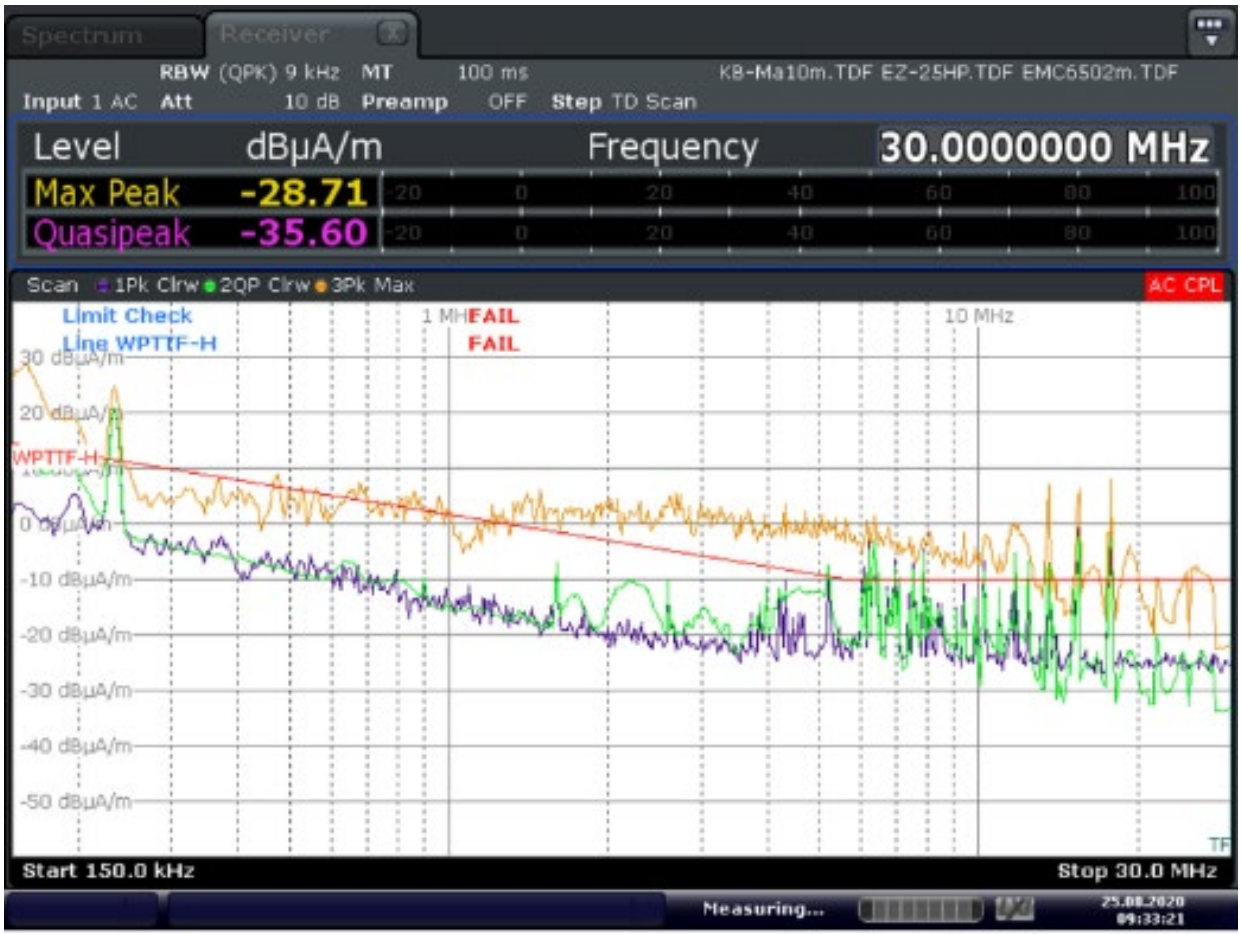


Figure 106: Example of Background emission (WPT off) 150 kHz – 30 MHz, axe X, charging location 1 (30 m), Time slot identification ID5

For easier presentation in this measuring report the three measurements for the three axes x, y and z were combined in one trace taking for each frequency the maximum value from the three results. Furthermore, measurements with WPT off and on were placed in the same graphics to allow for easier comparison.

A2.5.2.2 Magnetic Field Background Emissions

As the radiated emission measurements were done in situ and not in a semi anechoic chamber (SAC), the measurements include (besides the emission produced by the equipment under test) all wanted or unwanted emissions from the environment. A background emission measurement (with tested equipment turned off) gives an impression of the emission on a given time, but new disturbance sources can appear (or, less problematic, disappear) at each time. This makes the identification of the emission of the WPT more difficult, and even more when this emission is low.

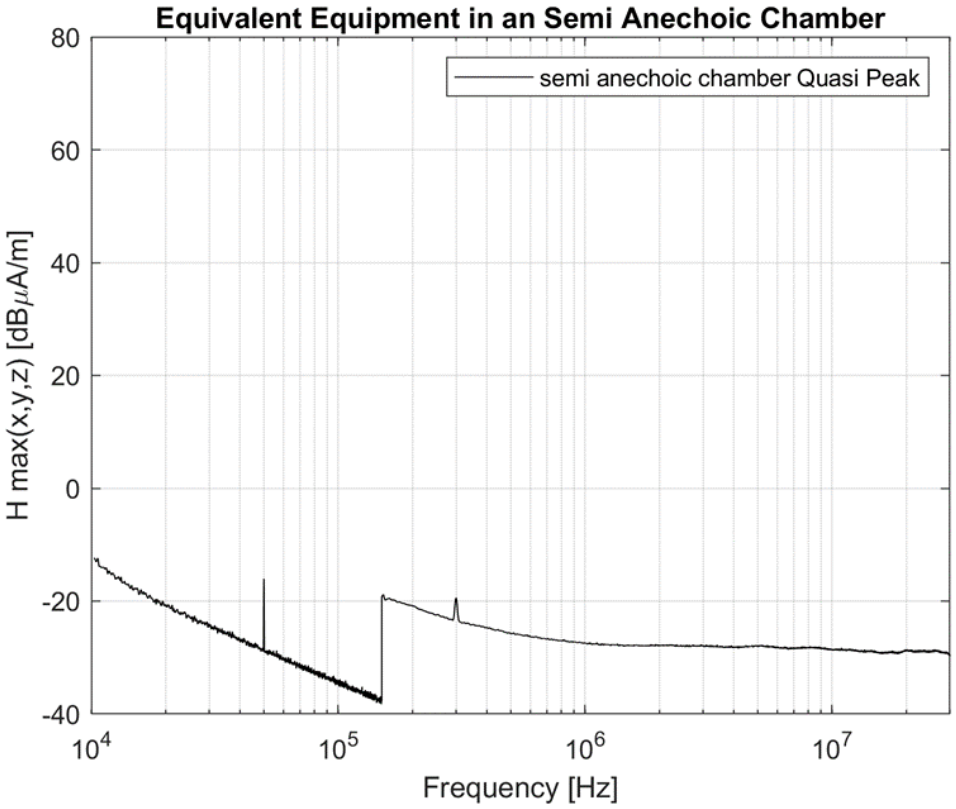


Figure 107: Measurement of equivalent test equipment in a semi anechoic chamber (SAC)

Two main sources of unwanted emission were identified at the measuring place, an electric fence (at 45 m) and power line communication (PLC) devices. These sources give a very broadband emission with high levels but are not permanently present. These sources could not be suppressed during the measurements. There is no statistic comparison to which the H-field background emission noise floor could be compared. For this reason, classification of the background emission at the specific place have been derived from the performance of the radio amateur communication.

The presence of these two disturbance sources explains some unusual characteristics in Figure 106. The actual peak measurement trace 1 (purple) shows the background emission in a time slot with no electric fence and no PLC. As the QP measurement trace 2 (green) takes longer time, it is much more unlikely to catch a time slot without PLC and fence signals. This explains the unusual situation that at some frequencies the QP value is higher than the actual Pk value. But the QP value is correctly always lower than the Pk max hold trace 3 (orange).

A2.5.2.3 WPT ON and OFF at Charging Location 1 (30 m Distance to Amateur Antenna 1)

Figure 110 and Figure 111 show the measured QP emissions with (blue line) and without (red line) WPT operation.

Figure 108 shows emissions from 10 kHz to 30 MHz. Figure 109 is an expanded version for HF from 5 MHz to 30 MHz. The difference between the WPT operating states ON and OFF are very low. Therefore, it can be expected that in this case (WPT System, background emission, etc.) the disturbances on amateur radio reception will probably be rather low. The red markers in Figure 110 to Figure 118 show where the harmonics of the basic frequency of the WPT are.

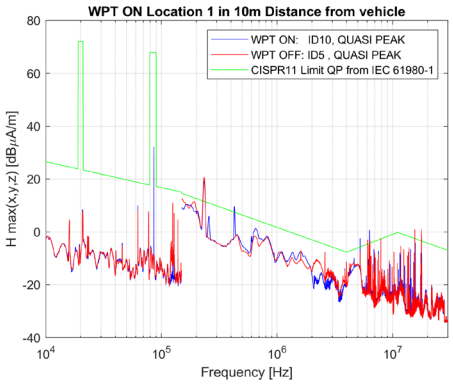


Figure 108: Emissions from 10 kHz to 30 MHz (LF to HF) measured with loop test antenna 10 m from WPT.

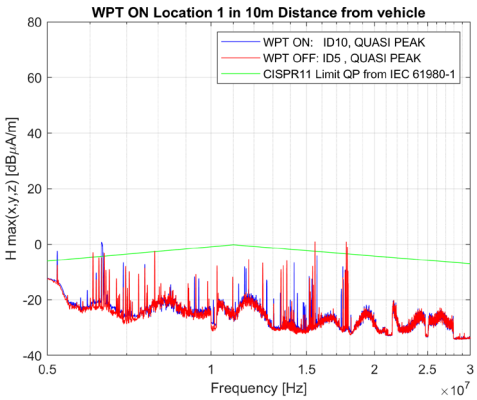


Figure 109: Expanded Fig. 19 for HF Emissions between 5 MHz to 30 MHz.

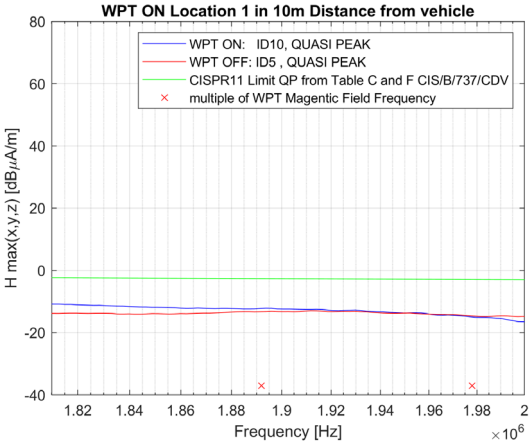


Figure 110: 160 m Band (1.81 to 2 MHz)

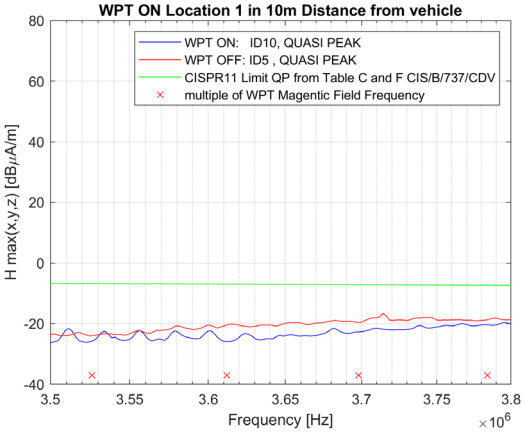


Figure 111: 80 m (3.5 MHz to 3.8 MHz)

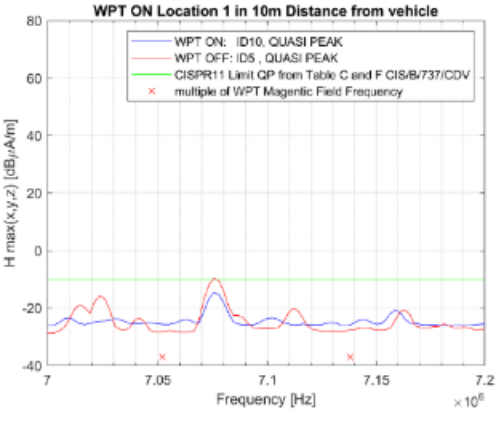


Figure 112: 40 m (7 MHz to 7.2 MHz) [6]

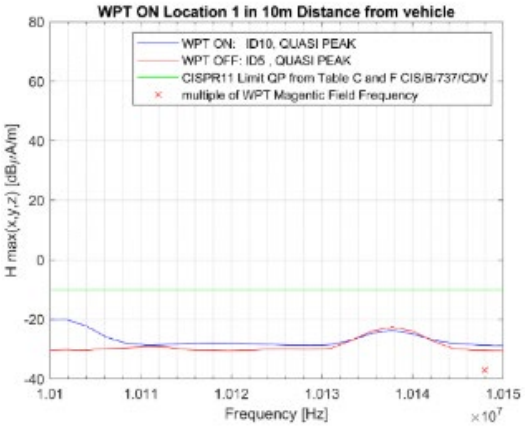


Figure 113: 30 m (10.1 MHz to 10.15 MHz) [7]

6 Class B CIS/B/737/CDV was rejected in CISPR.

7 Class B CIS/B/737/CDV was rejected in CISPR.

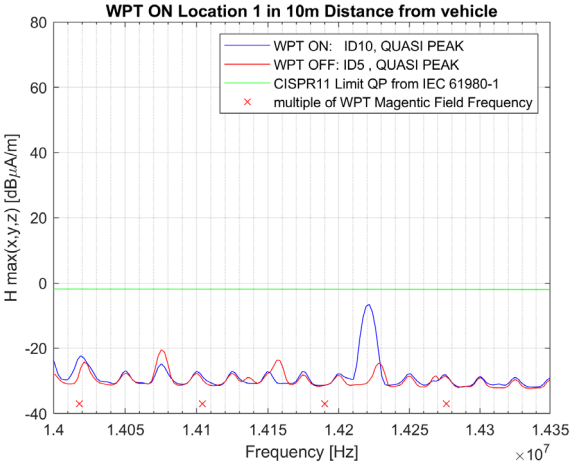


Figure 114: 20 m (14 MHz to 14.35 MHz)

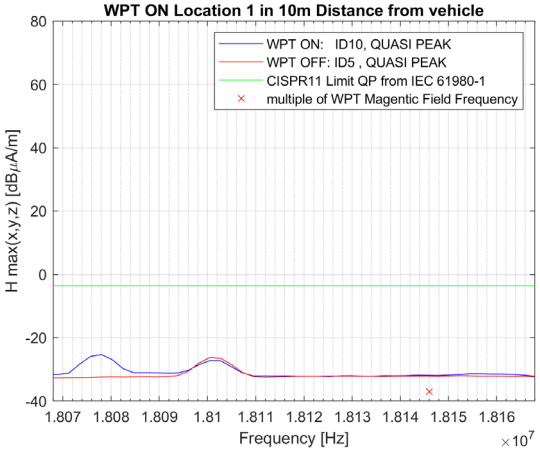


Figure 115: 17 m (18.068 MHz to 18.168 MHz)

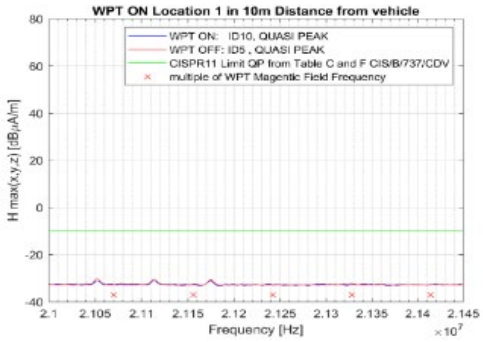


Figure 116: 15 m (21.0 MHz to 21.45 MHz) [8]

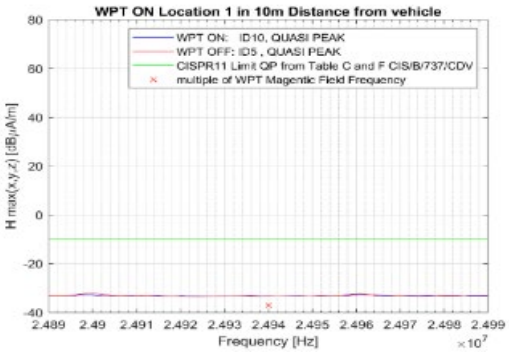


Figure 117: 12 m (24.890 MHz to 24.990 MHz) [9]

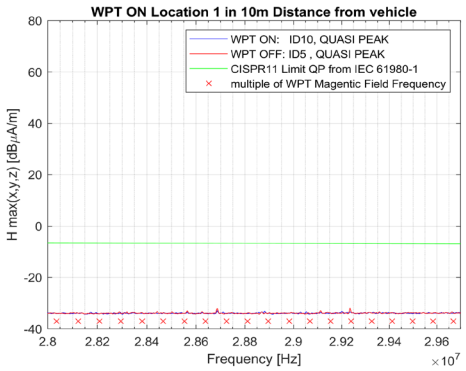


Figure 118: 10 m (28.0 MHz to 29.7 MHz)

8 Class B CIS/B/737/CDV was rejected in CISPR.

9 Class B CIS/B/737/CDV was rejected in CISPR.

Figure 114 is the only spectrum in which (with running WPT) there is an H-harmonic with H = -7 dBµA/m which is higher than -10 dBµA/m limits from IEC 61980-1 [7] and CISPR 11 [6] in the 20 m band. Because background emissions were changing over time and WPT ON and OFF cannot be measured at the same time, it is not clear whether the peak on the 40 m band is caused by the WPT.

A2.5.2.4 WPT ON and OFF at Charging Location 2 (11 m Distance to Amateur Antenna 1)

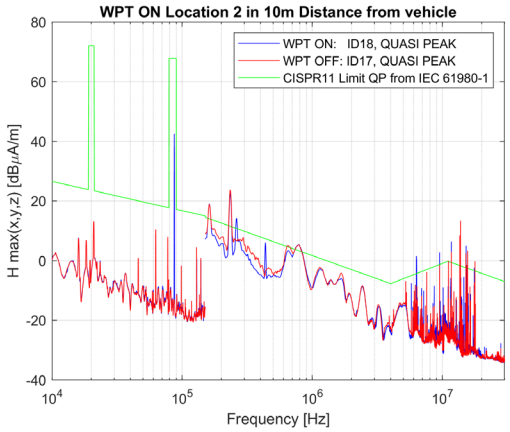


Figure 119: Emissions from 10 kHz to 30 MHz (LF to HF) measured with a loop antenna 10 m from WPT

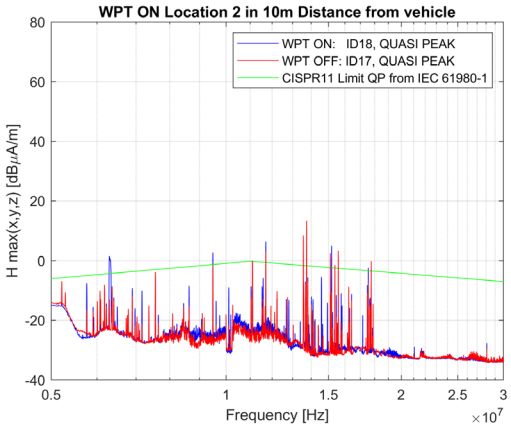
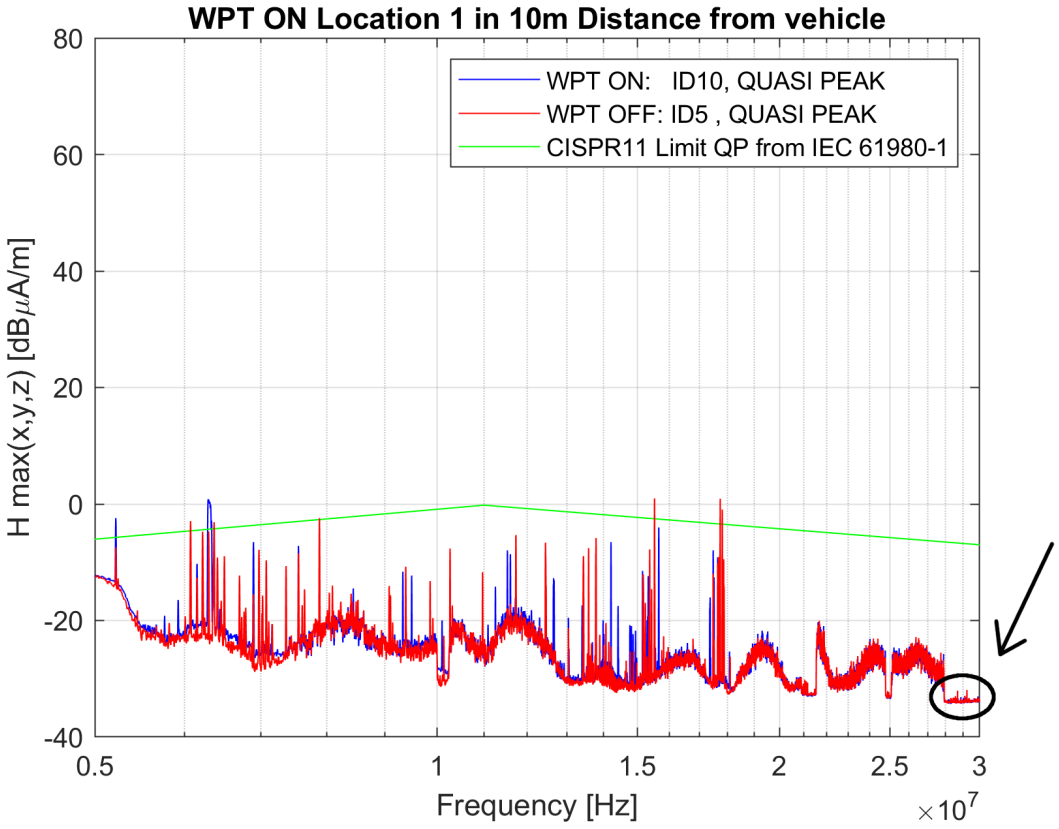


Figure 120: Expanded for HF Emissions from 5 MHz to 30 MHz

A2.5.2.5 Y-Component 27 MHz to 30 MHz



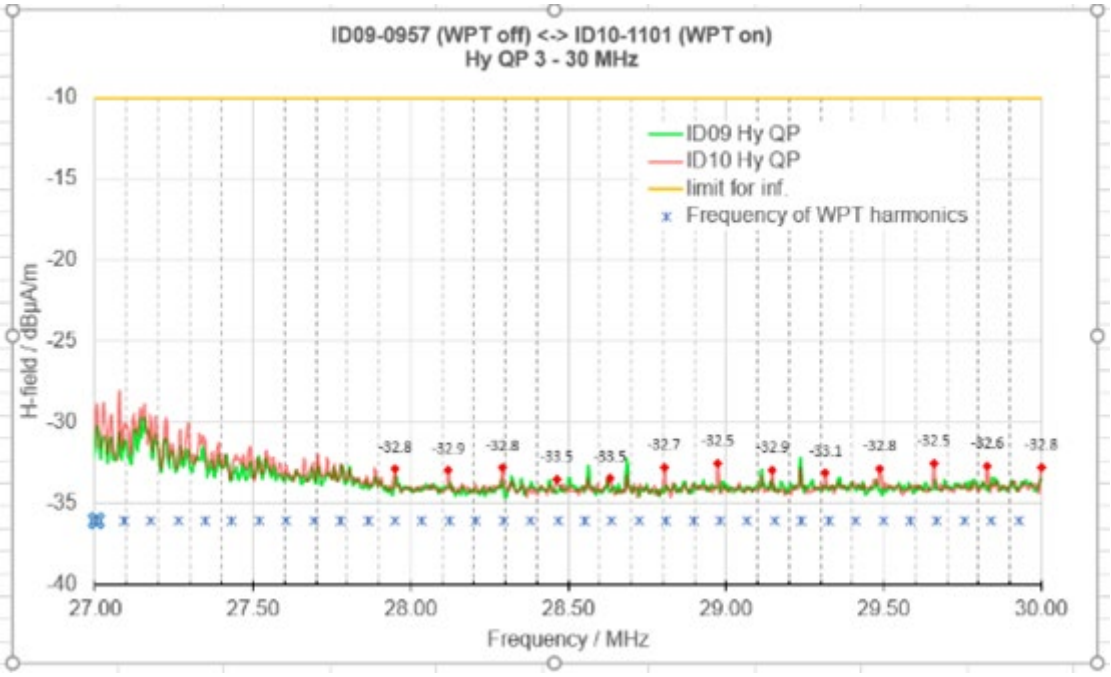


Figure 121: Zoom in only Y-Component 27 MHz to 30 MHz

By using only the Y-component of the measurement and zooming into an area with low background emission, the difference between WPT on and off can be measured. The takeaway is, that an emission of -33 dBµA/m had not significant influence on the radio amateur communication.

A2.5.2.6 Conclusion of Magnetic Field Strength Measurement

The emissions generated by the WPT system at frequencies above 150 kHz were comparable to the observed background emission, so that no clear distinction between the two, i.e. WPT system on or off, could be made. Since WPT OFF and WPT ON could not be measured at the same time and the background emissions shifted in frequency, it's possible that the measured peak between 14.2 MHz and 14.25 MHz was generated by another source than the WPT system. The 14.2 MHz signal was not visible with the IC-705 Receiver measurement, documented in following sections.

Like at charging location 1 also at WPT charging location 2 the difference between H-values for WPT on and WPT off is small. The distance between measurement equipment and WPT system was on both measurement setup the same.

A2.5.3 Interference to Radiocommunication services

To locate and assess nearby local disturbance sources on HF during periods of low solar activity, it is useful to use higher frequencies in this range, because there the number of transmitters is low due to low sky wave propagation. Therefore, at the beginning, often the spectra on 15 m and 10 m bands were recorded and used for a first assessment. For these spectra, frequencies often in the middle of the bands allocated to amateur radio were used. With spectra measured by means of the IC7600, which show the input signal at the receiver, mostly a reference yield of -50 dBm (except for the spectra at 7 MHz: -40 dBm), a RBW of 2.4 kHz, a vertical scale of 10 dB per division and beam direction NE were used. An RBW of 2.4 kHz was chosen in order to see the real impact of the WPT disturbance to SSB operation. The noise blanker of the IC7600 is very efficient and eliminates nearly all short impulses caused by the nearby farmer's electric fence (at 45 m and more). However, the spectrum analyzer FPC1000 from R&S does not have this feature and therefore records all these impulses.

A2.5.3.1 WPT at Charging Location 1 (30 m Distance to Radio Amateur Antenna 1)

All bands between 3.5 MHz and 29.7 MHz (80 m and 10 m) allocated to amateur radio were inspected at least by a careful manual scan. Due to space limitations, not all spectra can be shown here. All measurements with an effective distance of 35 m ($\sqrt{(17\ m)^2 + (30\ m)^2}$) were performed on 25 August 2020 before noon. Figure 122 to Figure 125 are examples of these measurements on 15 m band. Increasing QRN in the afternoon (example see Figure 124) made correct quantitative measurements impossible. These measurements were postponed to 23 September 2020.

WPT OFF



Figure 122: IC7600: ID25, 21.2 MHz, Span 200 kHz, BW 2.4 kHz, Max Pk -102 dBm = 5 dBµV

WPT ON



Figure 123: IC7600: ID10, 21.2 MHz, Span 500 kHz, BW 2.4 kHz, Max Pk -101 dBm = 6 dBµV (Radio traffic on 21.076 MHz)

WPT OFF



Figure 124: IC7600: ID17, 21.2 MHz, Span 200 kHz, BW 2.4 kHz
Max Pk -90 dBm = 17 dBµV ➔ QRN, too high!

WPT ON



Figure 125: IC7600: ID10, 21.2 MHz, Span 200 kHz, BW 2.4 kHz
Max Pk -101 dBm = 6 dBµV

In Figure 123, there is some radio traffic on 21.076 MHz, i.e. the signal level there is not caused by the WPT. With WPT at a horizontal distance of 30 m from beam antenna (height 17 m), spectra with WPT ON and OFF are nearly identical, no audible or in spectra visible interference of WPT on the 15 m band.

A2.5.3.2 WPT at Charging Location 2 (11 m Distance to radio amateur antenna 1)

Due to the local situation, a minimum horizontal distance of 10 m between the WPT at charging location 2 and amateur radio antenna 1 could not be realised exactly. Therefore, a minimum horizontal distance of 11 m was chosen instead of 10 m (effective distance to the antenna $\sqrt{(17\ m)^2 + (11\ m)^2} = 20.3\ m$).

Tests with IC7600 connected to antenna 1 (Beam)

15 m Band (21.0 MHz to 21.45 MHz):

WPT OFF



Figure 126: IC7600, ID28, 21.2 MHz, Span 500 kHz, BW 2.4 kHz
Max Pk -105 dBm = 2 dBµV

WPT ON



Figure 127: IC7600, ID27, 21.2 MHz, Span 500 kHz, BW 2.4 kHz,
Max Pk -103 dBm = 4 dBµV



Figure 128: IC7600, ID27, 21.2 MHz, Span 500 kHz, BW 2.4 kHz
Max Pk -103 dBm = 4 dBµV



Figure 129: IC7600, ID29, 21.2 MHz, Span 500 kHz, BW 2.4 kHz
Max Pk -103 dBm = 4 dBµV

With WPT at a horizontal distance of only about 11 m from beam antenna, spectra with WPT on and off are also nearly identical, no audible or in spectra visible interference of WPT on 15 m band. Possible remaining very low disturbance signals from the WPT could be buried in the local noise floor.

The overall electrical antenna factor of the 5-el. Beam for 21 MHz is about $AF_E = -11\ dB/m$. With measured values V (RX input voltage taken from spectrum) and using the equation $AF_E = E/V$, the E-field at the antenna can be calculated: $E = V * AF_E$ or in dB: $\boldsymbol{E[dB\mu V/m]} = \boldsymbol{V[dB\mu V]} + AF_E\ \boldsymbol{[dB/m]}$. A typical value according to Figure 128 and Figure 129 is $V = 4\ dB\mu V$, which gives $E = -7.5\ dB\mu V/m\ [peak\ value]$. For comparison of disturbance electrical E-fields at antennas of receivers are often indicated in dBµV/m.

20 m band (14 MHz to 14.35 MHz):

WPT OFF



Figure 130: IC7600, ID26, 14.2 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -98 dBm = 9 dBµV

WPT ON



Figure 131: IC7600, ID31, 14.2 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -97 dBm = 10 dBµV



Figure 132: IC7600, ID32, 14.2 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -98 dBm = 9 dBµV



Figure 133: IC7631, ID31, 14.2 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -98 dBm = 9 dBµV

During the measurement there was radio traffic on the 20 m band. Spectra for WPT ON and OFF are still somewhat similar, but there are no obvious differences between the OFF and ON diagrams (Figure 130 compared to Figure 131 and Figure 132 compared to Figure 133). For determination of the max Pk values indicated on the figures mostly the value of the max Pk strip (in blue, without traffic peaks) was used. The max peak level is somewhat higher than for the 15 m band. Actual noise level in ranges without traffic is flat and with no audible WPT harmonics. Only noise, no typical harmonics in the gaps between peaks caused by radio traffic. Comparable situation also on 40 m band (see figures below).

The overall electrical antenna factor of the 5-el. Beam for 14.2 MHz is about $AF_E = -13.5\,dB/m$. With measured values V (RX input voltage taken from spectrum) and using the equation $AF_E = E/V$, the E-field at the antenna can be calculated: $E = V * AF_E$ or in dB: $\boldsymbol{E[dB\mu V/m]} = \boldsymbol{V[dB\mu V]} + AF_E\ \boldsymbol{[dB/m]}$. A typical value according to Figure 132 and Figure 133 is $V = 9\,dB\mu V$, which gives $E = -4.5\,dB\mu V/m\ [peak\ value]$. For comparison of disturbance electrical E-fields at antennas of receivers are often indicated in dBµV/m.

40 m band (7.0 MHz to 7.2 MHz) at inverted V Antenna (top at 15 m):

WPT OFF

WPT ON



Figure 134: IC7600, ID34, 7.098 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -85 dBm = 22 dBµV (Ref. Yield -40 dBm)



Figure 135: IC7600, ID35, 7.098 MHz, Span 500 kHz, BW 2.4 kHz, max Pk -85 dBm = 22 dBµV (Ref. Yield -40 dBm)

The overall electrical antenna factor of the Inv. V antenna for 7.1 MHz is about $AF_E = -13\ dB/m$. With measured values V (RX input voltage taken from spectrum) and using the equation $AF_E = E/V$, the E-field at the antenna can be calculated: $E = V * AF_E$ or in dB: $\boldsymbol{E[dB\mu V/m]} = \boldsymbol{V[dB\mu V]} + AF_E\ \boldsymbol{[dB/m]}$. A typical value according to Figure 134 and Figure 135 Figure 133 is $V = 22\ dB\mu V$, which gives $E = 9\ dB\mu V/m\ [peak\ value]$. For comparison of disturbance electrical E-fields at antennas of receivers are often indicated in dBµV/m.

Spectra for LF < 140 kHz with IC7600 at Antenna 1 (inverted V):

Some tests were also carried out in order to see if some spectra with the fundamental frequency of the WPT equipment can be registered. The allowed band for WPT is 79 kHz to 90 kHz, which is pretty close to frequency of the time reference transmitter DCF77 at 77.5 kHz.

The signal of DCF77 could be easily detected in spectra (see peaks of about -95 dBm at 77.5 kHz). It can also detect audibly by tuning the receiver in SSB to a frequency around 77.5 kHz because it turns on and off in intervals of 1 s.

In the same spectra, there is also a signal at the fundamental frequency of the WPT operation. At this antenna it was very weak (about -100 dBm). During the test, the fundamental WPT frequency was about 88 kHz.

WPT Fundamental Frequency and DCF 77 measured with IC7600 at Antenna 1

WPT OFF



WPT ON



Figure 136: IC7600, ID36, DCF77 on 78 kHz, -95 dBm, fundamental frequency of WPT field 88 kHz off, max Pk of DCF 77 about -95 dBm = 12 dBµV.

Figure 137: IC7600, ID35, DCF77 on 78 kHz, fundamental frequency of WPT field 88 kHz on, max Pk of WPT ca. -100 dBm = 7 dBµV.

E-Field Background Emission

- The antenna factor of the antenna 1 is known. This enables to calculate the E-field background emission measured by the antenna 1 as following:
- $E_{@\ 7.1\ \mathrm{MHz}} = +9\ dB\mu V/m$ (Measured Background Emission with 2.4 kHz Bandwidth)
- $E_{@\ 14.2\ \mathrm{MHz}} = -4.5\ dB\mu V/m$ (Measured Background Emission with 2.4 kHz Bandwidth)
- $E_{@\ 21\ \mathrm{MHz}} = -7.5\ dB\mu V/m$ (Measured Background Emission with 2.4 kHz Bandwidth)

The below figure from Recommendation ITU-R P.372 [25] depicts the noise figure Fa as function of frequency 0.2-300 MHz:

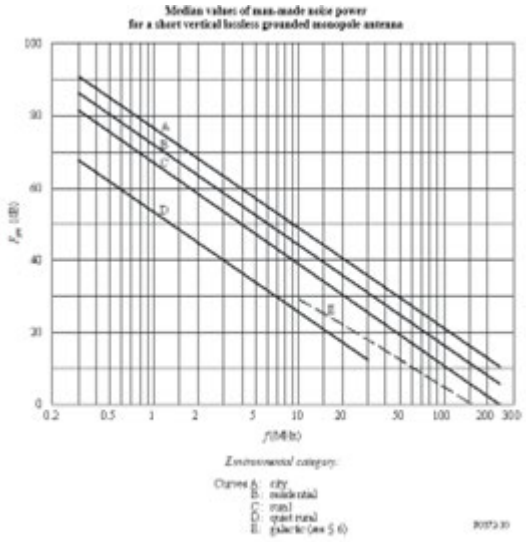


Figure 138: Median values of man-made noise

For a short (h << l) vertical monopole above a perfectly conducting ground plane, the vertical component of the r.m.s. field strength is given by:

$$En = Fa + 20\ log\ fMHz + B - 95.5\ dB(\mu V/m)\ where\ B = 10\ log\ [bandwidth\ (Hz)]$$

For the used 2.4 kHz bandwidth: $En = Fa + 20\ log\ fMHz - 61.7\ dB(\mu V/m)$

7 MHz: En = 48 + 20 log (7) - 61.7 = + 3.2 dBµV/m (Residential background emission according ITU-R)

14 MHz: En = 40 + 20 log (14) – 61.7 = + 1.2 dBµV/m (Residential background emission according ITU-R)

21 MHz: En = 36 + 20 log (21) – 61.7 = + 0.7 dBµV/m (Residential background emission according ITU-R)

Table 21: Comparison background emissions measured on Side and expected in residential situation according ITU-R

	Measured E-Field Background Emission on Antenna 1	Residential Background Emission according Recommendation ITU-P.372-17 [28]
7 MHz	+ 9 dBµV/m	+ 3.2 dBµV/m
14 MHz	- 4.5 dBµV/m	+ 1.2 dBµV/m
21 MHz	- 7.5 dBµV/m	+ 0.7 dBµV/m

Tests with Spectrum Analyzer FPC1000 Connected to Antenna 1 (Beam)

As mentioned previously, at a distance > 45 m of the QTH of HB9AZO there is an electric fence surrounding a grazing field for cattle. This fence is connected to a device creating about every second a short high voltage peak. Therefore, this fence radiates many short impulse disturbances which are picked up by radio amateur antenna 1. While in the IC7600 an efficient noise blanker eliminates nearly all these impulse disturbances, the FPC1000 has not this feature and therefore records all these peaks. Therefore, the spectra do not look very nice because the curves have many very sharp peaks.

An approximation of the development of the undisturbed curves can be obtained by clipping these sharp peaks of the max peak hold curve over 10 s (green) and actual value (yellow) in the Figure 139 and Figure 140. It seems that in the direction of the main lobe of the beam (NE) for this measurement there is probably a PLC or VDSL2 transmission in the neighbourhood.

In both spectra the amateur band from 21.0 MHz to 21.45 MHz is notched as it should be according to the requirements of the regulation authority and the relevant PLC standards. At higher and lower frequencies, the signals are about 20 dB higher and would disturb reception. In Figure 140 the PLC or VDSL2 signals for < 21 MHz are nearly on the same level like in the notch. The full bandwidth of the VDSL2 system is obviously not always used but seems to depend on time or on traffic intensity.

WPT OFF



Figure 139: FPC1000, ID26, 20.7 – 21.7 MHz , Span 1 MHz, BW 3kHz, max Pk about 4 dBµV at 21 MHz decreasing to 0 dBµV at 21.45 MHz. 15 m Amateur band notched.

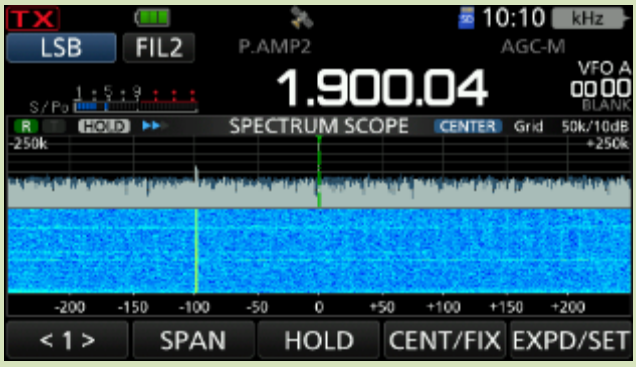
WPT ON

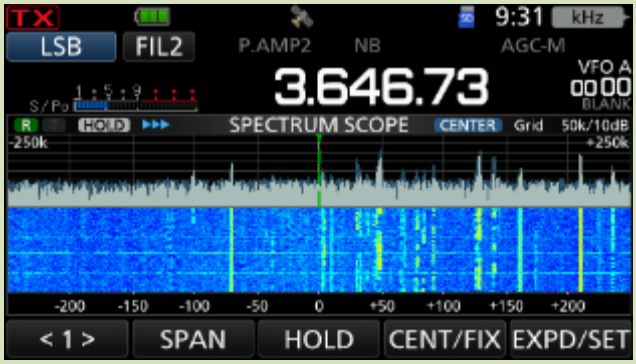


Figure 140: FPC1000, ID29, 20.7 – 21.7 MHz, Span 1 MHz, BW 3 kHz max Pk about 0 dBµV at 21 MHz decreasing with frequency to -3 dBµV at 21.45 MHz. 15 m amateur band notched.

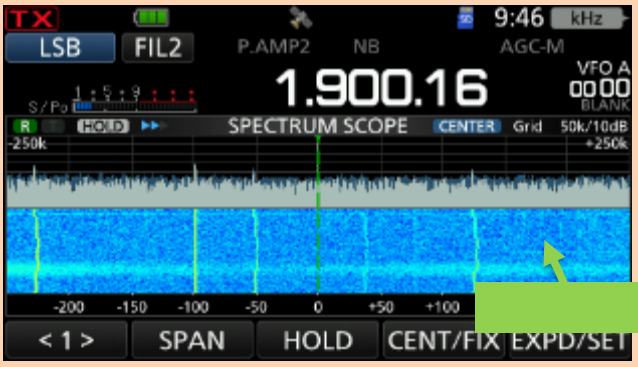
Tests with IC-705 on Antenna 2 (Loop) at 10 m distance from WPT

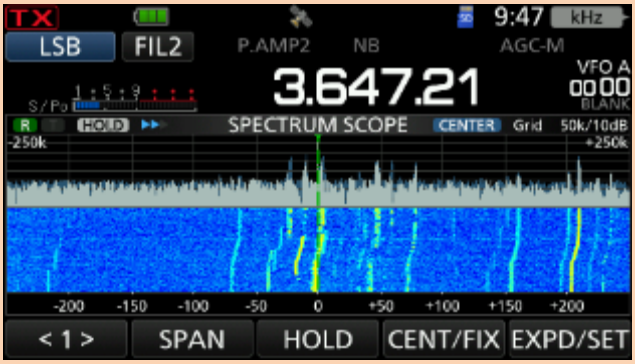
WPT OFF





WPT ON





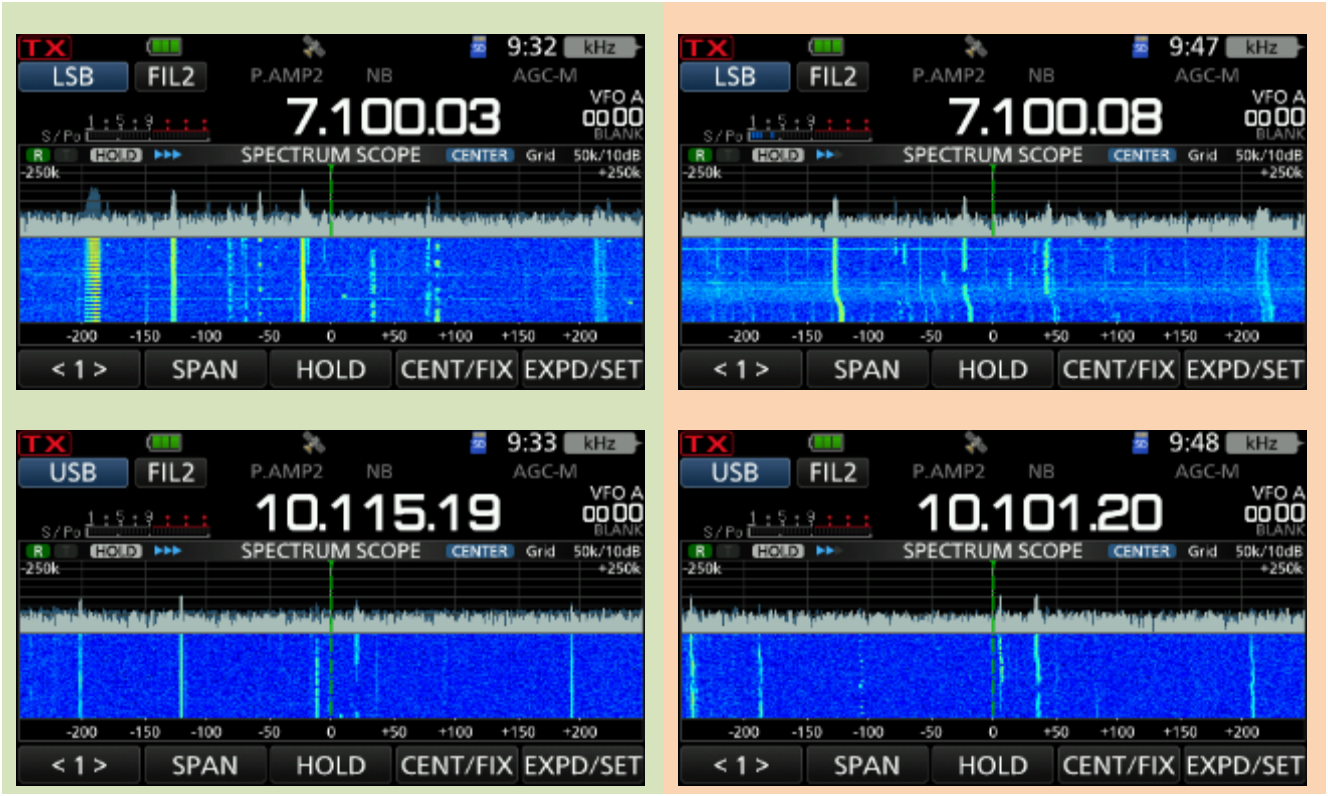
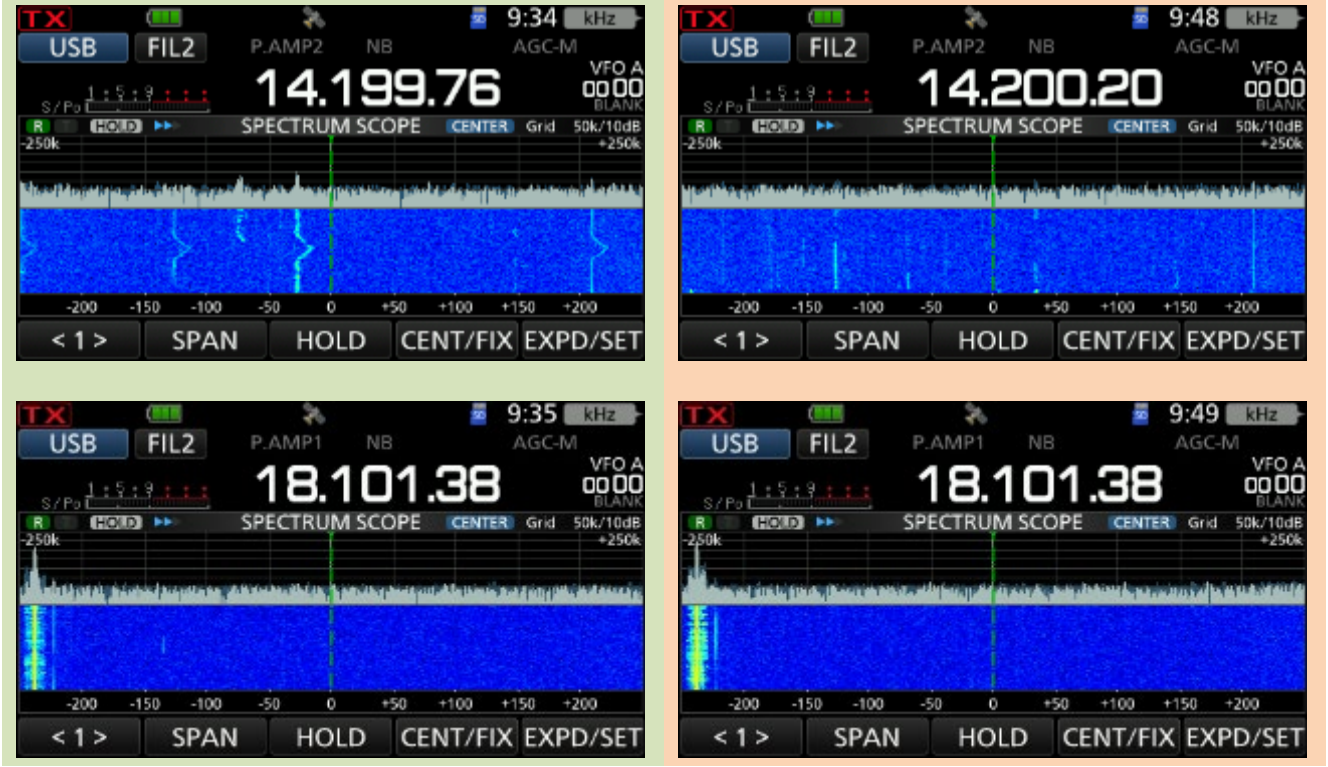


Figure 141: IC-705 on antenna 2 on all amateur bands (1.8 MHz – 10.2 MHz)

WPT OFF

WPT ON



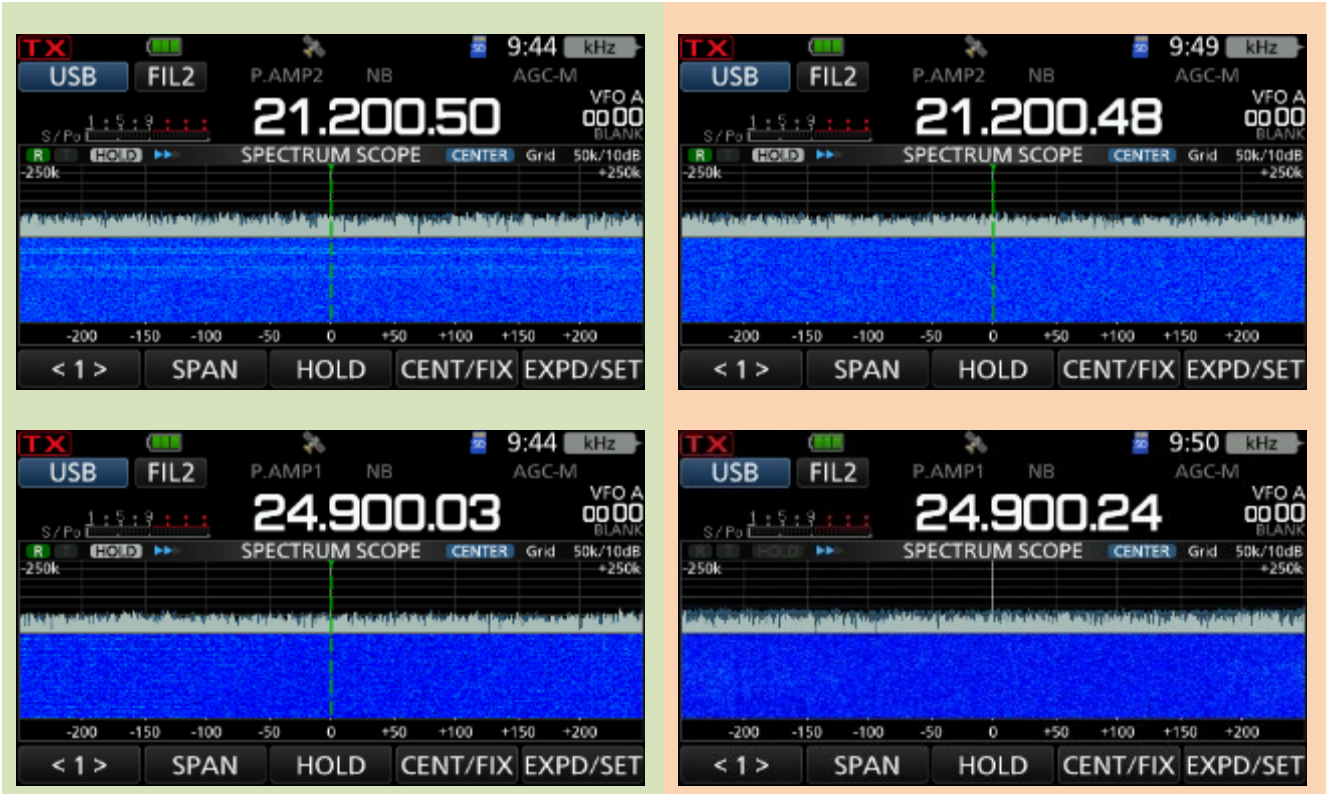


Figure 142: IC-705 on antenna 2 all amateur bands (14.0 MHz – 25 MHz)

WPT OFF

WPT ON

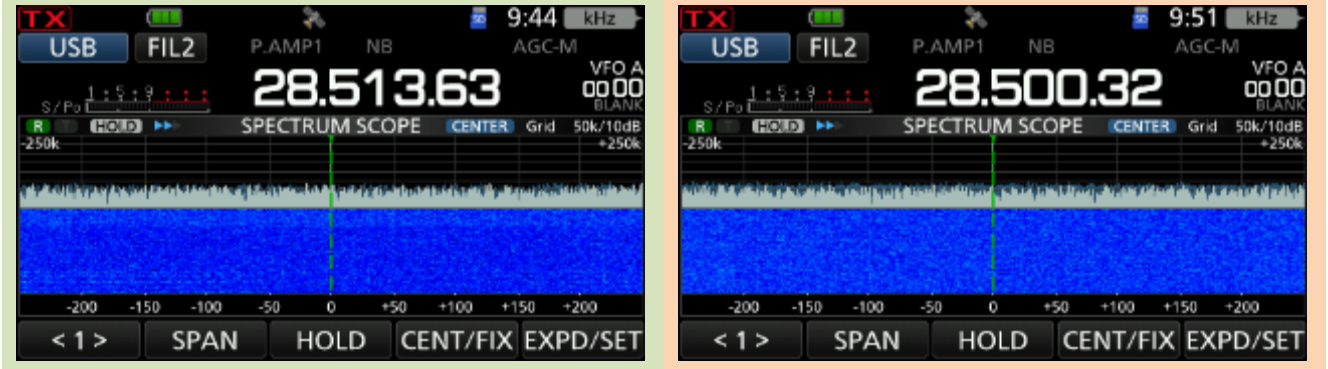
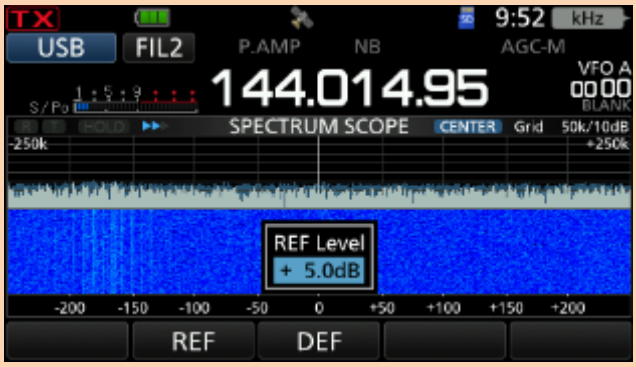


Figure 143: IC-705 on antenna 2 (28 MHz)

WPT ON



WPT ON

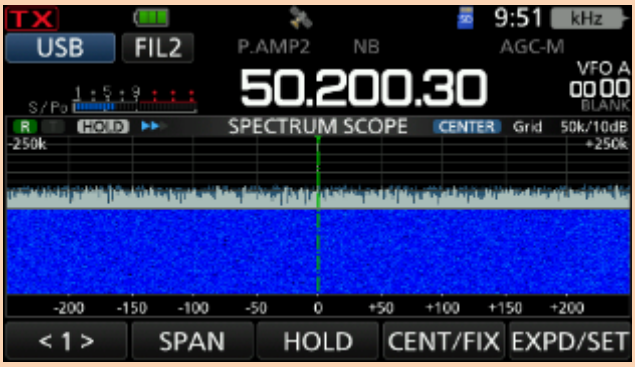


Figure 144: IC-705 on antenna 2 (50.2 MHz and 144 MHz)

A2.5.3.3 Conclusion

Only in the diagrams for 1.900 MHz for WPT OFF and WPT ON some signals for WPT ON can be recognised as harmonics of the WPT f1.

For basic frequency f1 = 88 kHz (Figure 137):

- for n=21 -> f21 = 1850 kHz;
- for n=22 -> f22 = 1938 kHz;
- for n=23 -> f23 = 2026 kHz..

The background emission floor regularly surpassed the signals generated by the WPT system on a broad-spectrum disturbance, marked with a green arrow.

A2.5.3.4 DCF77 Measured with IC-705 on Antenna 2 (10 m Distance to WPT System)

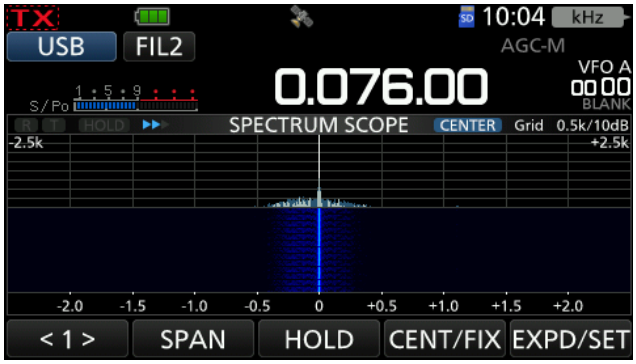


Figure 145: DCF77 on magnet field antenna 2 (RX set to lower sideband)

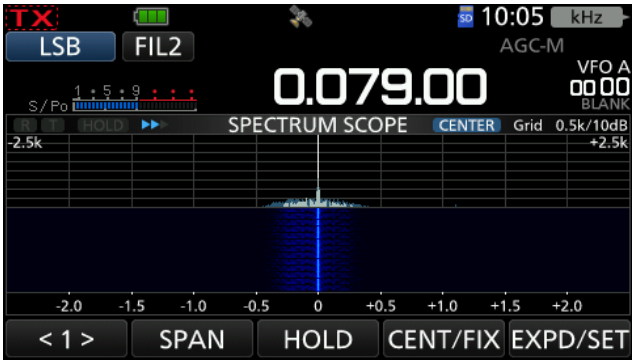


Figure 146: DCF77 on magnet field antenna 2 (RX set to upper sideband)

The DCF77 Signal was clearly measurable and not influenced by the main magnetic field generated from WPT system. The DCF77 is a 77.5 kHz signal. The Icom IC-705 shows the carrier frequency +/- 1.5 kHz from the LSB (lower sideband) or USB (upper sideband). This is the reason why the receiver showed 76 kHz and 79 kHz on the frequency display when receiving the DCF77. With an appropriate receiver the DCF77 would be properly detected in the measured situation.

The antenna factors of the LOOP antenna 2 on the bands shown are unknown. Therefore, amplitude measurements with it can only give qualitative results and cannot be used for direct comparison. The active loop radio antenna 2 showed similar sensitivity as the full-size beam antenna 1 at frequencies above 10 MHz,

but is less sensitive than a half-wave dipole typically used by AR stations in the bands 1.8 MHz, 3.5 MHz and 7 MHz. A signal at the fundamental frequency f1 of the magnetic field of the WPT could be received very weak (-100 dBm) with the inverted V antenna at position 1 and the WPT in 10 m horizontal distance (Figure 124). Unfortunately, no picture was made with the LOOP antenna 2 and IC-705 showing the WPT-signal on f1. The main magnetic field generated by the WPT system could also be measured at 10 m as about 42 dBµA/m (see Figure 119). This would not affect amateur radio and be allowed according to new proposals for limits for H-field from IEC 61980-1 [7] and CISPR 11 [6] see green line on all figures between Figure 108 and Figure 120.

There was no interference from WPT on f1 = 88 kHz to the time signal of DCF77 observed (not specially tested).

A2.6 COMPARISON OF H AND E FIELD MEASUREMENTS

Comparing near field magnetic emission levels with electrical background emissions would be incorrect if the free space impedance is used to convert between the two.

Figure 147 shows how the distance from the WPT-EV significantly influences the conversion factor between H and E field for on a specific Antenna. Therefore, this study does not compare low frequency dipole antenna electric field measurements directly with the magnetic field measurement.

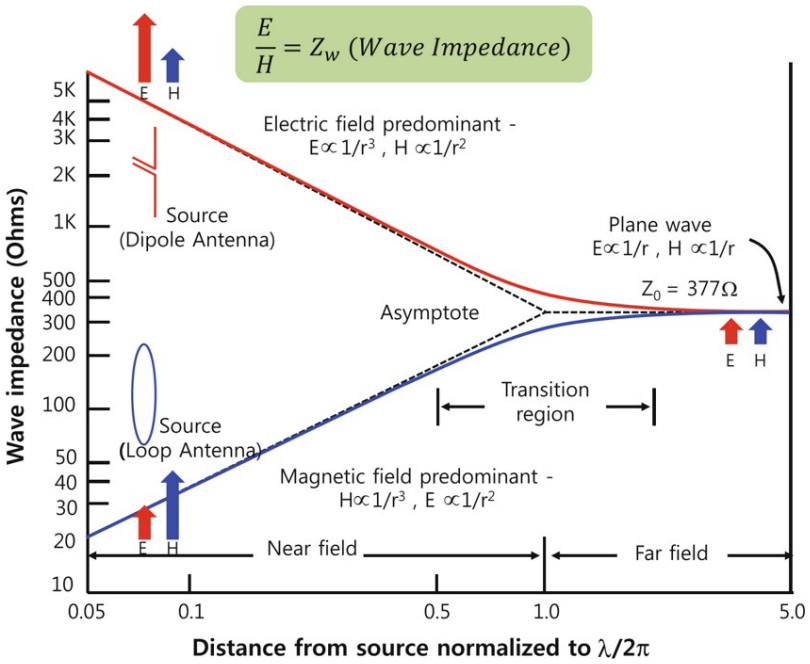


Figure 147: Free Space Impedance [38]

A2.7 DISCUSSION OF POSSIBLE REASONS FOR THE RESULTS OBSERVED

In course of repeated discussions about WPT limits between members of the Swiss national CISPR committee, the idea was born to obtain practical measurement results at a location with a typical amateur radio station with moderate equipment owned by one of the members (HB9AZO), where there were good possibilities for interference measurements with WPT sources at distances between 10 m and 30 m. The situation of this location (see section A2.4.1, Figure 96, Figure 97and Figure 98) was similar to a typical situation in the UK shown in figure 2 in [35] or figure 31 in [37]. These measurements were especially interesting because besides the measurements with amateur equipment also magnetic field measurements at the same time. As mentioned before, besides all the tests described in detailed in section A2.5.3, also manual scans with a bandwidth (BW) of 2.4 kHz (mode: LSB for f < 10 MHz, USB for f > 10 MHz) on the entire bands 80 m, 40 m, 30 m, 20 m, 17 m, 15 m, 12 m and 10 m were carried out. The EMC noise generated by the operating WPT system at

frequencies above 150 kHz was comparable or even lower to the observed background emission. Therefore, no clear distinction between the two conditions, i.e. WPT system ON or OFF, could be made.

A2.7.1 Results of all tests in the configuration and location described in section A2.3

The measurements revealed no interferences at the receiver of the amateur radio station caused by the WPT system. Even though the residential environment and the test setup are typical and represent a realistic scenario, this result cannot be generalised in the sense that interferences can never occur. Other environments and setups (e.g. antennas, positions, distances, receiver properties) may produce other results.

A2.8 CONCLUSIONS AND OUTLOOK

No interferences could be observed during this trial between the WPT system and amateur radio communication in a residential environment with moderate man-made disturbances. The DCF77 signal was received with good quality on the radio amateur antennas. With an appropriate receiver, the main magnetic field generated by the WPT system would not disturb the DCF77 even close to the charging vehicle.

Measurements using the magnetic loop antenna showed a peak at the WPT operating frequency, which was clearly discernible from the background emission. The EMC noise generated by the WPT system at frequencies above 150 kHz was comparable to the observed background emission, so that no clear distinction between the two, i.e. WPT system on or off, could be made.

These measurements suggest that a properly designed inductive charging system for electric vehicles would not disturb radio communication in a residential environment. This result, however, should not be generalised. More field trials could be carried out to confirm the conclusions made in this study.

Furthermore, this Report does not draw any conclusions about the potential impact of widespread WPT systems use on amateur radio communications. Further work could include measurements with multiple systems active at the same time.

ANNEX 3: ASSESSMENT OF MEDIAN SIGNAL LEVELS IN THE AMATEUR SERVICE

In considering the potential impact of WPT devices on radio communications systems, the typical level of signals in the relevant radiocommunications service is an important input in considering protection issues. This section of the Annex provides information about signals measured with receiver in the amateur bands, drawn from off-air measurements, and overlays as reference points the spurious emission limits defined in CISPR 11 [7].

A3.1 MEASUREMENT OBJECTIVES

The measurements set out to determine two things:

- The general level of signals in the amateur service. There are no minimum service levels defined in the amateur service and it is a “low power signal” service. The off-air measurements conducted provide detail on the actual levels of signal in everyday communication;
- The background noise level at the rural test site[10].



Figure 148: Location of the rural test site

Equipment used comprised the following:

- A wideband calibrated SDR receiver RSP1A: https://www.sdrplay.com/docs/RSP1Adatasheetv1.9.pdf
- SDR software giving access to FFT length data to allow accurate conversion of measurements to other bandwidths: https://www.sdrplay.com/docs/SDRplay_SDRuno_User_Manual.pdf
- Spectrum analyser Anritsu MS2034B: https://www.anritsu.com/en-us/test-measurement/products/ms2034b
- A calibrated signal source Elecraft XG3: https://elecraft.com/products/xg3
- A vertical monopole - Titanex V160HD (feed point at ground level)
- A vertical monopole for 10 MHz (feed point 1 m above ground)
- A three-element Yagi antenna (SteppIR 3-element yagi) at 12 m above ground
- A screened 50Ω termination resistor

[10] 52.480301 N, 2.856970 W - England

- Three sets of measurements were taken:
- The noise level with the input to the receiver terminated with 50Ω
- The noise level with the antenna connected
- The spectrum of signals with the antenna connected

In carrying out these tests, it became evident that measurements of background noise levels using an SDR are not straightforward, and that care is needed to understand how the relevant SDR software process the signal in order to display the spectrum. Initial tests with two types of SDR software (SDR# and SDR Console) yielded inaccurate results. These software packages did not allow access to the FFT data and so misleading noise bandwidth data was measured. A third software package and SDR (RSP1A) gave full information on the FFT length and resulting measurement bandwidth which was validated as accurate to within the measurement accuracy of the system.

Measurements are only presented for the 1.8-14 MHz amateur bands as the maximum impact of WPT emissions is expected in this part of the spectrum.

A3.1.1 Measurement steps

A3.1.1.1 Calibration

A calibrated 50Ω signal source was injected into the receiver on each frequency band measured at various levels. The levels were compared with the dBµV scale on the receiver. The tracking from 0 dBµV to +74 dBµV was seen to be well within +/- 1 dB.

A3.1.1.2 50Ω termination

The system noise was measured to confirm that the receiver noise factor would not influence the overall measurement integrity. The measurements confirmed a suitably low level of receiver noise to conduct valid measurements, with inherent noise being at least some 15 dB or more below off-air background noise.

A3.1.1.3 Off-air measurements

Vertical monopoles were generally used for the off-air measurements (but a 3-element Yagi antenna 7.4 dBi forward gain was used for 14 MHz). They had antenna factors as shown in the below table. The table also notes the off-air background noise at the test site.

Table 22: Antenna factors of the antennas used in the tests

Frequency (MHz)	Antenna	Gain in dBi	Gain (G) multiple	Antenna factor in dB/m*	Background noise dBµA/m
1,8	Vertical monopole	0	1.00	-24.7	-56.1
3,5	Vertical monopole	0	1.00	-18.9	-56.0
7	Vertical monopole	1.2	1.32	-14.1	-58.3
10	Vertical monopole	0	1.00	-9.8	-56.1
14	3 element Yagi	7.4	5.5	-14.0	-60.6

Spectrum plots were then taken of amateur service traffic, together with a note of the background RMS noise level. Measurements were taken late afternoon with the exception of 1800 kHz where the measurements were taken in the evening to ensure presence of radiocommunications traffic. However, checks were taken at other

times of the day to ensure that the data presented is suitably representative. There are times of day when signal levels are significantly lower than shown.

A3.1.2 Results

Spectrum scans were taken for the 1.8, 3.5, 7, 10.1 and 14 MHz amateur bands. As an example, the scan for the 7 MHz amateur service spectrum is shown below.

Conversion of all data has been carried out to ensure that a consistent RBW is used for all data.

It will be noted that the general level of signals and signal/noise ratio is broadly consistent with that shown in ECC Report 289, figure 30 [37], which suggests mean level of signals in the amateur service of 15-20 dB above noise level. For the purpose of this study, scans have been recorded using both a vertical monopole and a magnetic loop.

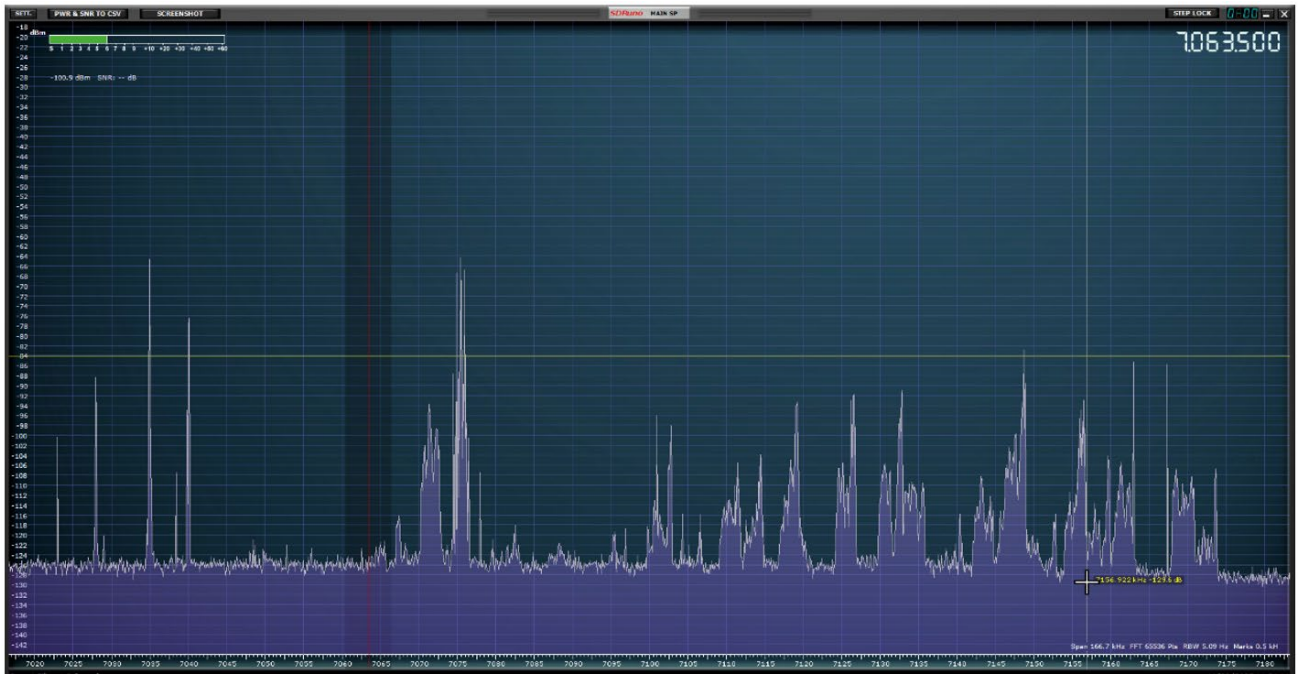


Figure 149: 7 MHz spectrum - vertical monopole:
FFT BIN: 5.09 Hz Measurement bandwidth 3 kHz AF -14.1 dB/m

The measurements were then repeated using a magnetic loop antenna of known Antenna Factor of 4.8 dB/m. The spectrum plot for the 7 MHz spectrum is shown below. From this it will be noted that, after allowing for antenna factor differences, the general level of signals is comparable with the measurements made with the vertical monopole.

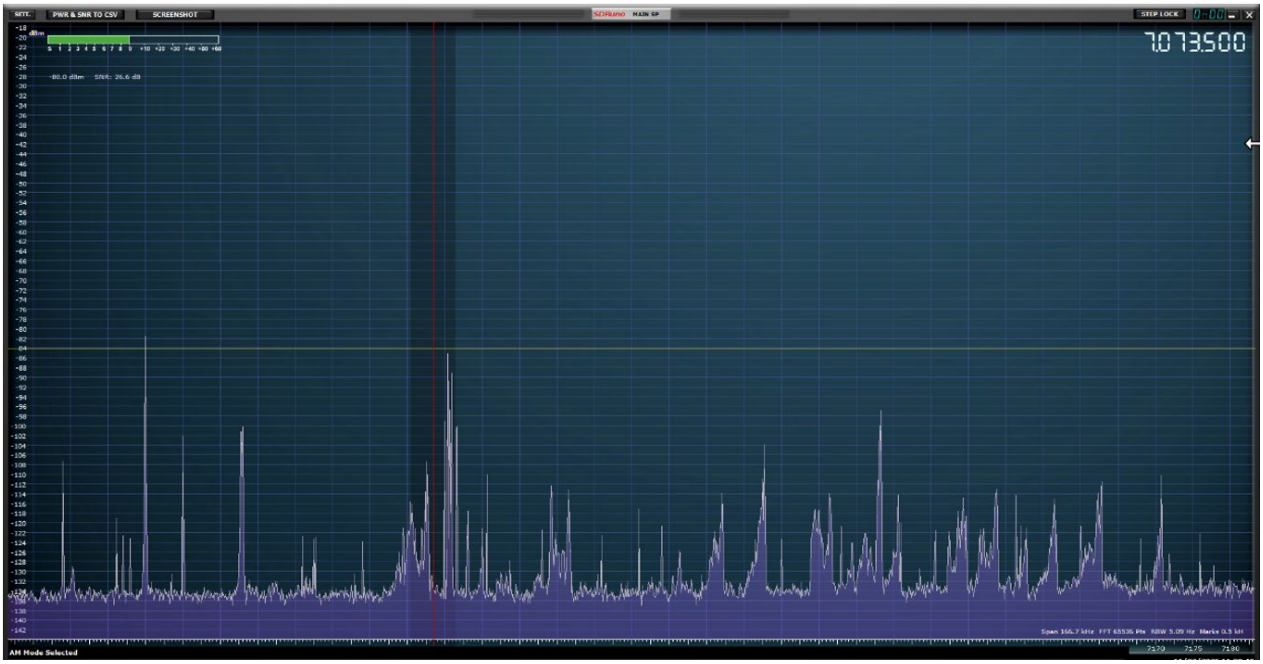


Figure 150: 7 MHz spectrum - loop antenna:
FFT BIN: 5.09 Hz Measurement bandwidth 3 kHzAF +4.8 dB/m

Deriving the noise levels for each plot for 500 Hz communications bandwidth (A1A or data communication):

- Monopole: -125 dBm in RBW of 5.09 Hz.
  - In 500 Hz = -125 + 10*log (500/5.09) = -105.1 dBm
  - In dBuV -105.1+107 = 1.9 dBuV = -49.6 dBuA
  - In dBuA/m -49.6 + AF = -63.7 dBuA/m

- Loop: -134 dBm in RBW of 5.09 Hz.
  - In 500 Hz = -134 + 10*log (2300/5.09) = -114.1 dBm
  - In dBuV -114.1+107 = -7.1 dBuV = -58.6 dBuA
  - In dBuA/m -58.6 + AF = -53.8 dBuA/m

These results can be taken as being representative of the measurements made in other parts of the amateur spectrum in the study provided in this Report. The study has measured the typical levels of signals in the amateur service bands between 1.8 and 14 MHz. It shows a broadly consistent result, from which it will be seen that:

The measured level of signals in one rural location in the amateur service bands indicated have S/N ratios of some 10-30 dB at the receiver with a median of some 20 dB. Median signal levels were typically -45 dBuA/m.

According to measurements from a receiver at one location, emissions at the limits of ERC Recommendation 74-01 [5] at a measurement distance of 10 m could exceed the levels of amateur service signals by 10-30 dB or more when using a magnetic loop antenna.

When using a vertical monopole E-field antenna, the comparative levels cannot be stated for sure. For 7, 10 and 14 MHz at least, 10 m spacing places the antenna in the far field and so emissions are likely to be close to the H-field levels converted using free-space impedance but will be attenuated by the reduced gain of the monopole including the effects of low elevation angles.

ANNEX 4: COMPARISON OF H-FIELD LEVELS DISCUSSED IN THIS REPORT

Several H-field levels have been discussed and referenced in this Report. The below figure gives an overview (which is not exhaustive) of those.

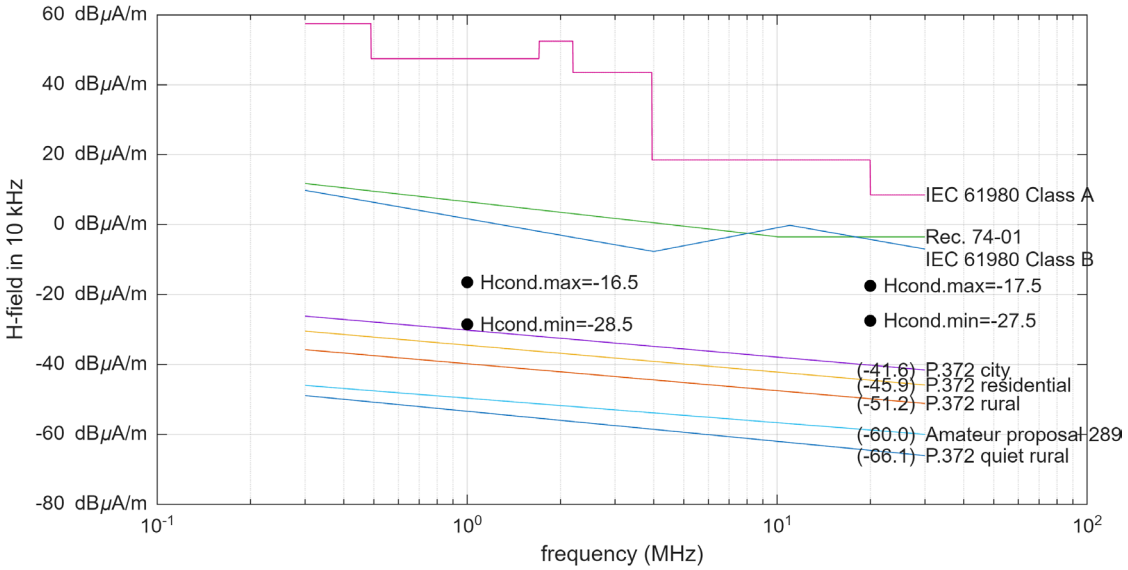


Figure 151: Comparison of emission relevant levels

A4.1 COMPARISON WITH CONDUCTED CHARGING

Systems that may be comparable in terms of device density, location of usage and power levels are conducted chargers. Measurements have been done in 2025 for conducted charging of WPT-EVs in order to observe the emissions in the band 9 kHz to 30 Mhz. For 6 different vehicles the emissions were observed in 3 m distance. In order to compare them to limits in 10 m distance, a conversion factor needs to be applied. CISPR derived this factor in IEC CDV 61000-6-3/AMD1/FRAG3 ED3. This factor is about 27 dB decreasing to 10 dB at 20 MHz and above.

Following figures present both extreme results of this measurement. Results for the other systems are in between both plots shown.

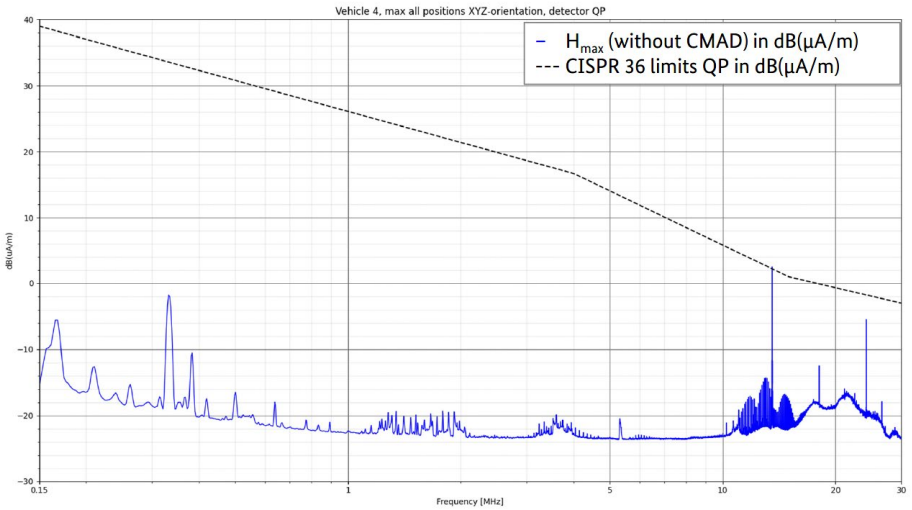


Figure 152: Measurement result for conducted charging - best case

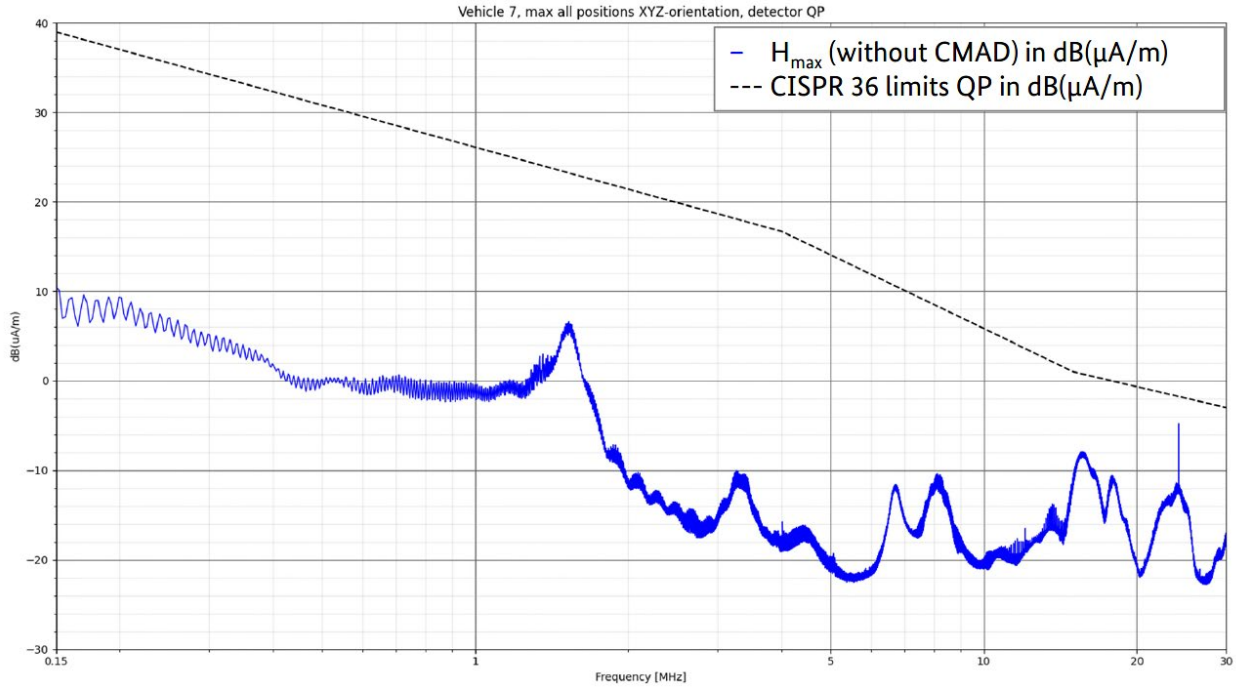


Figure 153: Measurement result for conducted charging - worst case

In the frequency range of about 20 MHz a conversion to the distance of 10 m must be applied of 10 dB, which leads to conducted charging emissions between -28 dBµA/m in 9 kHz and -18 dBµA/m in 9 kHz.

In the frequency range below 1 MHz a conversion to the distance of 10 m must be applied of 27 dB, which leads to conducted charging emissions between -29 dBµA/m in 9 kHz and -17 dBµA/m in 9 kHz.

Converting those numbers to a bandwidth of 10 kHz, 0.5 dB need to be added. Both reference ranges are also depicted in Figure 151.

ANNEX 5: IMPACT OF UNWANTED EMISSIONS OF WPT ON THE MARITIME SERVICE

A5.1 INTRODUCTION

A5.1.1 Summary

Wireless power transfer equipment in the kW range is expected to supply power to the charging/power management systems of electric vehicles, with typical frequency ranges around 20-25 kHz and 80-90 kHz depending on vehicle type.

WPT is intended to operate in closely coupled configurations, if there is sufficient egress of RF energy from such inductive energy transfer then there is a possibility to interfere with the reception of nearby radio receiving installations. The effects may be noticeable in analogue radio systems operating in the LF and MF bands on frequencies on or harmonically related to the nominal operating frequency of inductive power transfer equipment. Assessment of the interference potential needs accurate knowledge of the minimum field strength requirement for the radio system in question and the protection requirement.

A5.1.2 Introduction to the maritime systems

Maritime safety information is broadcast by coast stations on 490 kHz and 518 kHz and are identified in the Radio Regulations, Appendix 15 as part of the Global Maritime Distress and Safety System (GMDSS). These are commonly referred to as NAVTEX services.

The potential to interfere with maritime radiocommunication and radionavigation systems was noted in Report ITU-R SM.2451 [48], Assessment of impact of wireless power transmission for electric vehicle charging on radiocommunication services, though without any specific findings – indeed, it is noted in § 4.1.9 of the Report that the “Impact from WPT-EV to the maritime mobile service requires study”. A comprehensive revision of this Report has just taken place in ITU-R Study Group 1 and the revised § 4.1.4 of the Report notes information relevant to NAVTEX and some other maritime radio systems as result of measurements on high WPT-EV installations reported in Annex 2 to the revised Report.

Although no conclusions are drawn from those studies, the emission levels measured from the experimental WPT system at 10 m were noted.

There are also references to emission levels from other types of WPT equipment on frequencies used by maritime radio systems, including NAVTEX, in the national studies reported in Report ITU-R SM.2303 [47], Wireless power transmission using technologies other than radio frequency beam. However, no conclusions are made in respect to the impact of such emissions.

A5.1.2.1 Technical parameters of NAVTEX (Navigational)

NAVTEX operates at 518 kHz and 490 kHz using FSK signalling in a 300 Hz bandwidth with a typical sensitivity of 2μV. These are GMDSS prescribed frequencies in the ITU Radio Regulations [14].

A5.1.2.2 Technical parameters of DSC (Digital selective calling)

DSC operates in MF band at 2187.5 kHz using FSK signalling in a 300 Hz bandwidth with a typical sensitivity of 2μV. This is a GMDSS prescribed frequency in the ITU Radio Regulations [14].

A5.1.3 Background

For radio systems using analogue modulation techniques, compatibility issues can be addressed to a first approximation by treating the egress of RF energy from magnetic induction power transfer equipment as if an unmodulated electromagnetic wave propagating in the near-field region. Limits on RF radiation from for WPT equipment are usually presented in terms of an allowable magnetic field at distances of 3 to 10 metres. This

means that the assessment of the impact on radio receiving installations would involve conversions between magnetic and electric field strengths in order to determine the impact on the radio system in question.

The 518 kHz NAVTEX transmissions correspond to a wavelength of 578.75 m, which means that it is not easy to design or mount an efficient antenna on board ship, The usual solution is to use a short vertical active antenna sensitive to the electric field component of NAVTEX transmissions This does give some advantage in that the magnetic field drops off rapidly, according to the cube11 of the distance, in the near-field region. However, there is also the complication of needing to add the conversion factor of 51.5 dBΩ to the stray magnetic fields when comparing the wanted to the unwanted electric field strength, according to the formula:

$$E_{dB(\frac{\mu V}{m})} = H_{dB(\frac{\mu A}{M})} + 51.5\ dB(\Omega)$$

This conversion factor is derived from the impedance of free space, Z0, 377 Ω, from which 20•log10(377) = 51.5 dBΩ.

Relevant extracts concerning NAVTEX from the two Reports ITU-R SM.2303 [47] and Report ITU-R SM.2451 [48] are provided below for reference.

A5.1.4 Report ITU-R SM.2451 [48] (Annex 2 - Magnetic field strength measurements)

Measurements were conducted on an experimental heavy duty WPT-EV bus system in Gumi City, Korea. The system operates with its fundamental in the 19-21 kHz frequency range and has a third harmonic in the 55 - 65 kHz frequency range which is used as part of the power transfer. Details of the emission measurements are contained in the below table.

Table 23: Details of the emission measurements

Radiocommunication services and systems	Frequency bands	Test results (dBuA/m) at 10 m
Maritime radio	90-110 kHz (LORAN / eLORAN)	26.73 (100.2 kHz)
	424 kHz, 490 kHz, 518 kHz (NAVTEX)	-10.7 (423 kHz) -10.8 (488 kHz) -11.3 (518 kHz)
	495 kHz - 505 kHz (NAVDAT)	-11.5 (500 kHz)

The first task in assessing the risk of interference to NAVTEX reception is to confirm the wanted electric field strength and a suitable protection ratio.

Associated with all the studies involving NAVTEX was CCIR Report 910, Sharing Between the Maritime Mobile Service and the Aeronautical Radionavigation Service in the Band 415-526.5 kHz. This Report is still in publication as Report ITU-R M.910-1. The following extract is relevant to the analysis here:

This Report provides the following information on the operational requirements for a NAVTEX receiving installation in the context of avoiding interference to reception:

*"*With consideration of minimum atmospheric noise levels, the minimum field strength in which a NAVTEX receiving installation can be expected to work is 18 μV/m (25 dB μV/m).

The required co-channel wanted signal to unwanted signal protection ratio is assumed to be 1 dB for the purpose of this example (this value needs further study, see the following Note).

---

[11] The cube law decay of the magnetic field in the near-field region is explained in Recommendation ITU-R SM.2028 [11] and in ERC Report 69 [10] (*Propagation Model and Interference Range Calculation for Inductive Systems 10 kHz - 30 MHz*).

Note: The Regional Administrative Radio Conference for the Maritime Mobile Service, and the Aeronautical Radionavigation Service in certain parts of the MF band in Region 1 (Geneva, 1985) established the co-channel wanted signal to unwanted signal."

The first version of the Report differed in taking the minimum field strength to be 5μV/m 14(dB(μV/m)) (see Annex I to Draft Report 910(MOD I) contained in Annex III to the CCIR Report to RARC-85 [80]).

However, the reference to the need for further work regarding the protection ratio and the Planning Agreement developed for RARC-85 leads to the following information on the field strengths to be used for planning purposes in the Final Acts of RARC-85.

The protection ratio for planning between NAVTEX and similar services was taken as 8 dB. Therefore, two approaches need to be considered in determining a limit for the strength of the disturbance field at the antenna of a NAVTEX receiving installation.

Table 24: Attenuation due to frequency offset of NAVTEX systems

Frequency difference relative to 518 kHz (kHz)	Attenuation (dB)
0.0	0
0.6	3.0
1.0	11.6
1.5	50.0
2.0	70.0
3.0	110.0

Where the radiation from WPT does not include components exactly on one of the national or international NAVTEX frequencies, the protection ratio drops off rapidly so that disturbance is not likely to occur.

A5.2 STUDY A: IMPACT OF "UNWANTED EMISSIONS OF WPT DEVICES" ON THE MARITIME SERVICE

A5.2.1 Methodology

In study A, minimum separation distances between WPT antennas and antennas of the maritime service are calculated in the near-field region, which can be assumed up to the distance of λ/(2 π) [9] and [5].

Following victim systems are considered:

- DGNSS @ 300 kHz;
- NAVDAT @ 500 kHz;
- NAVTEX @ 500 kHz;
- MF Voice @ 2182 kHz.

For the transmitter's level of emissions ERC Recommendation 74-01 [5], table 6 Reference number 2.1.3 (Short range inductive devices operating below 30 MHz) is used. The units are given in dBμA/m at 10 m distance in 10 kHz. The receiver's maximum level of interference is derived from its specific sensitivity, which is given in dBμV/m. A far field conversion between both units cannot simply be done, because scenarios are assumed where interferer and victim are relatively close to each other. In those scenarios near field conditions apply, which means that the impedance of a magnetic loop is low and inductive and can be approximated according to Z ~ 2370 Ω * r / λ, limited to 377 Ohms [9]. Furthermore, a simplified environment without any

conducting obstacles is assumed, which in reality have an impact on the fields. Additional measurements could be conducted to confirm this model of conversion for this specific use case.

The propagation model for near field environments is derived from ERC Report 69 [9] (formulas on page 7). This is based on ideal models of magnetic loops.

The results were obtained from coplanar-direction plots, but are considered valid also for the coaxial direction. This is justified for two reasons:

1 The propagation model is based on ideal loop antennas without a vehicle positioned above. Under these assumptions, the maximum emissions are expected in the coplanar direction. It's limit in this study would still based on ERC Recommendation 74-01;

2 Both the coplanar and coaxial components follow similar attenuation in the near field.

A5.2.2 Study between WPT-EV and DGNSS @ 300 kHz

DGNSS systems are used to allow maritime navigation to be more accurate than using GNSS systems only. E.g. they are used for navigation in coastal, estuary and harbour areas as well as on inland waterways.

According to Recommendation ITU-R M.823-3 [40], DGNSS systems are deployed in the frequency range 238.5 kHz to 315 kHz.

This study assumes unwanted emissions from WPT systems at the frequency of 300 kHz at a field strength of ~ 11.8 dBµA/m @10 m in 10 kHz, according to ERC Recommendation 74-01 [5]. For the receiving bandwidth of 0.5 kHz this value is calculated to -1.3 dBµA/m @10 m in 0.5 kHz.

Figure 154 shows the roll-off function of the H-field that is assumed in the near-field region, following a drop of 60 dB/decade [8]. The calculation is based on ERC Report 69 [9]. At lower distances than 374 m the coaxial direction of the fields can be assumed as worst case. At higher distances than 374 m the coplanar direction of the fields can be assumed as worst case. The level of emissions at 10 m distance is highlighted. The near field ends at λ/2pi = 159 m. Results shown beyond this distance are not relevant for this study.

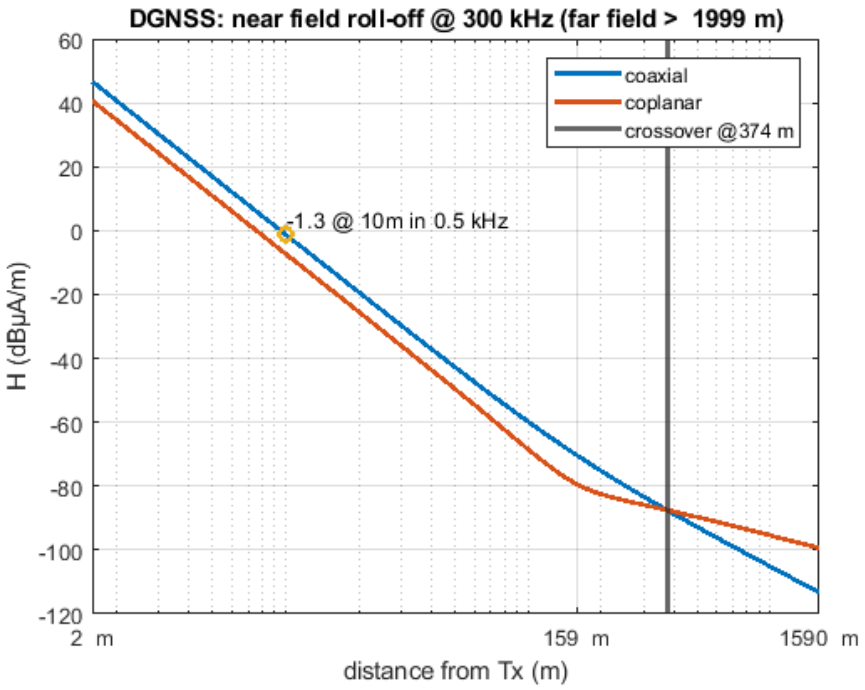


Figure 154: Roll-off function of H at 300 kHz

According to Recommendation ITU-R M.823-3 [40], the DGNSS' dynamic range is given as electrical field.

In the near field, the impedance of a magnetic loop is low and inductive and can be approximated according to Z ~ 2370 Ω * r / λ [7], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 155. For distances above 159 m results would be applicable for H-field antennas as victim. As an example, at 50 m distance the conversion factor used would imply 10 dB less sensitive E-field antennas compared to H-field antennas with regard to H-field interference.

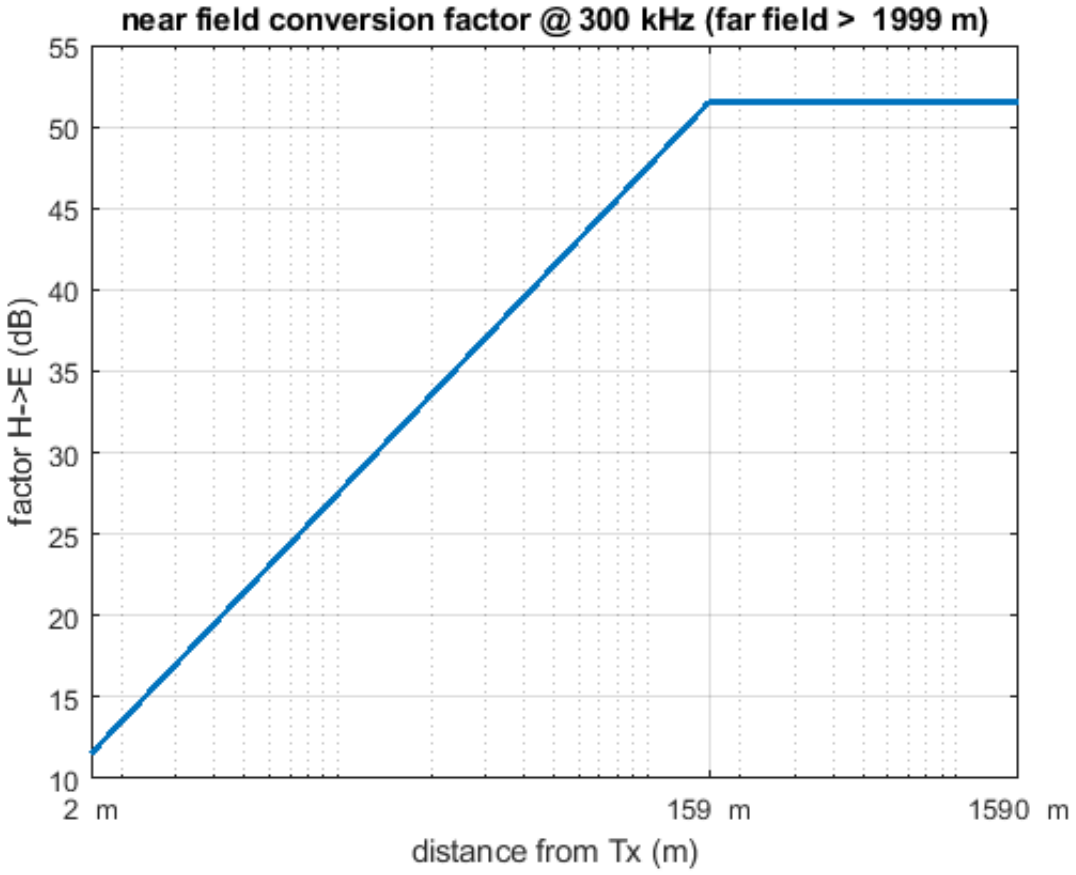


Figure 155: Near field conversion factor between magnetic and electric fields

The dynamic range of a DGNSS system starts with 10 µV/m in 0.5 kHz in linear, 20 dBµV/m in logarithmic scale. 7-15 dB of SNR is needed. Thus, 5-13 dBµV/m in 0.5 kHz is assumed to be the maximum allowed level of interference.

Figure 156 shows the E field. It is based on the H field and the conversion was applied. For inductive loop transmitters, the E field is following a drop of 40 dB/decade in the near-field region [5]. The minimum distances at which the interference criteria are respected are highlighted. At the distance of 22 m, the SNR of 7 dB is respected, at the distance of 34 m the SNR of 15 dB is respected.

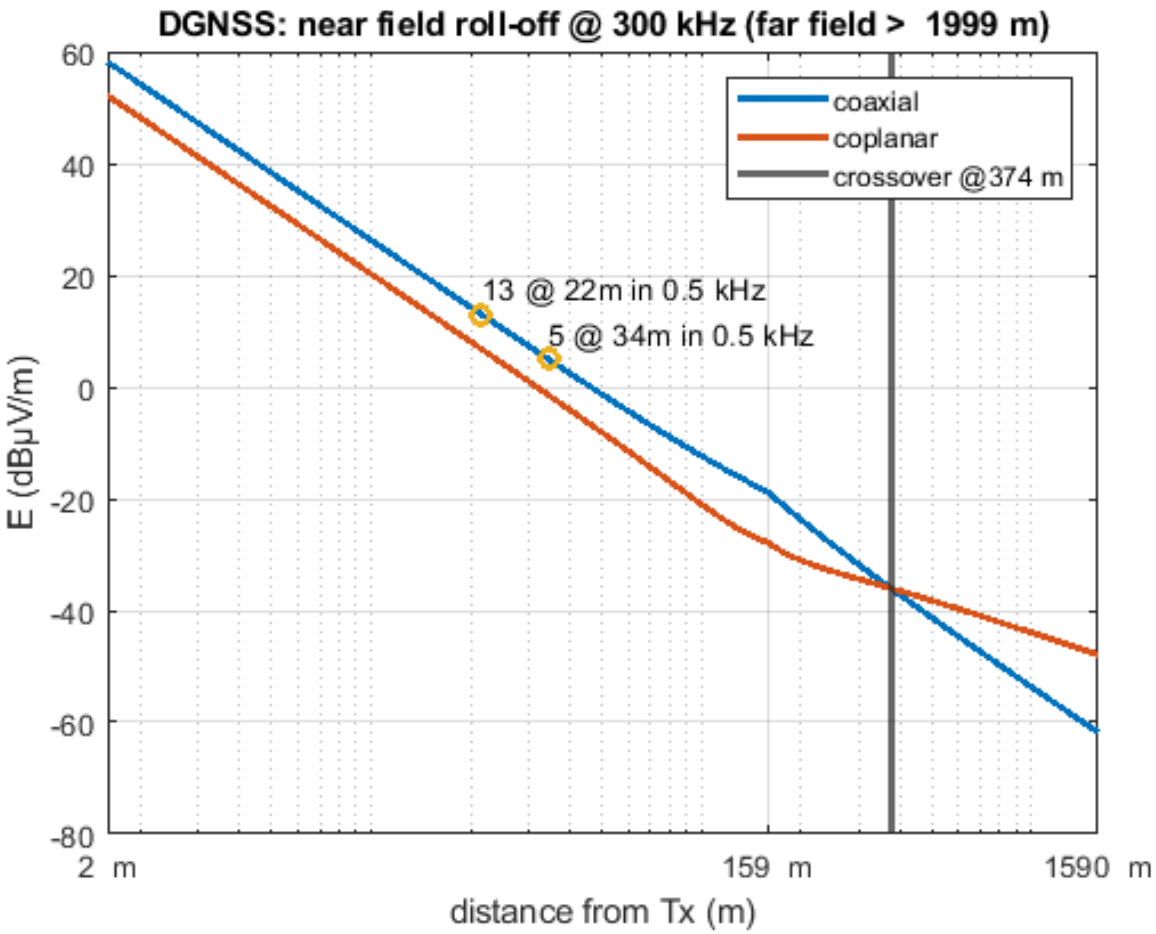


Figure 156: Roll-off function of E-Field at 300 kHz

A5.2.3 Study between WPT-EV and NAVDAT @ 500 kHz

According to Recommendation ITU-R M.2010-2 [42] NAVDAT systems are deployed in the frequency range 495 kHz to 505 kHz.

This study assumes unwanted emissions from WPT systems at the frequency of 500 kHz at a field strength of ~ 9.5 dBµA/m @10 m in 10 kHz according to ERC Recommendation 74-01 [5].

Figure 157 shows the roll-off function of the magnetic field that is assumed in the near-field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [9]. At lower distances than 225 m, the coaxial direction of the fields can be assumed as worst case. At higher distances than 225 m, the coplanar direction of the fields can be assumed as worst case. The level of emissions at 10 m distance is highlighted. The near field ends at λ/2pi = 95 m. Results shown beyond this distance are not relevant for this study between WPT-EV and NAVDAT @ 500 kHz.

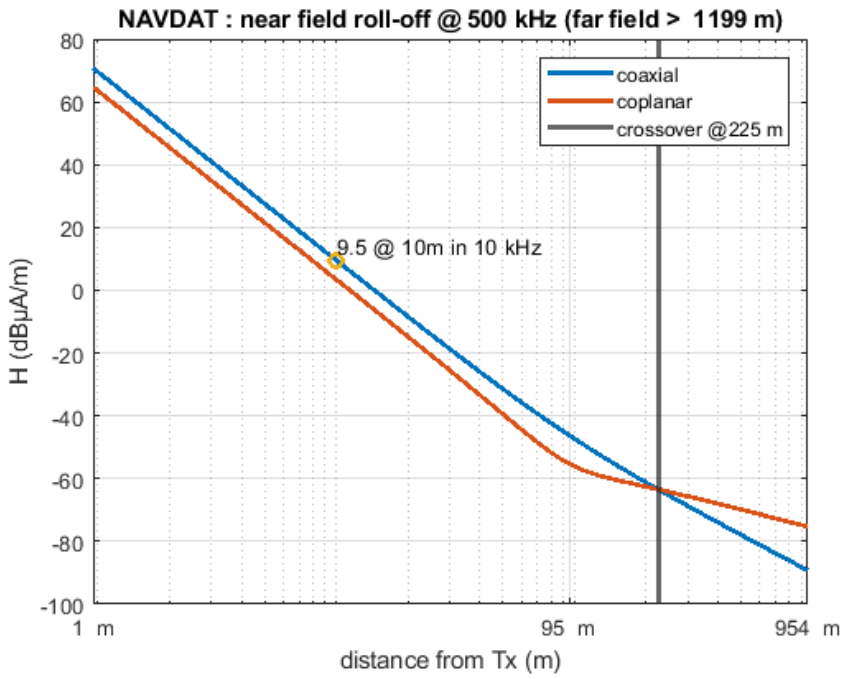


Figure 157: Roll-off function of the magnetic field at 500 kHz

According to Recommendation ITU-R M.2010-2 [42] the NAVDAT's sensitivity is given as an electric field of 25 dBµV/m in 10 kHz.

In the near field, the impedance of a magnetic loop is low and inductive and can be approximated according to Z ~ 2370 Ω * r / λ [7], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 158. For distances above 95 m results would be applicable for H-field antennas as victim. As an example, at 50 m distance the conversion factor used would imply 4 dB less sensitive E-field antennas compared to H-field antennas with regard to H-field interference.

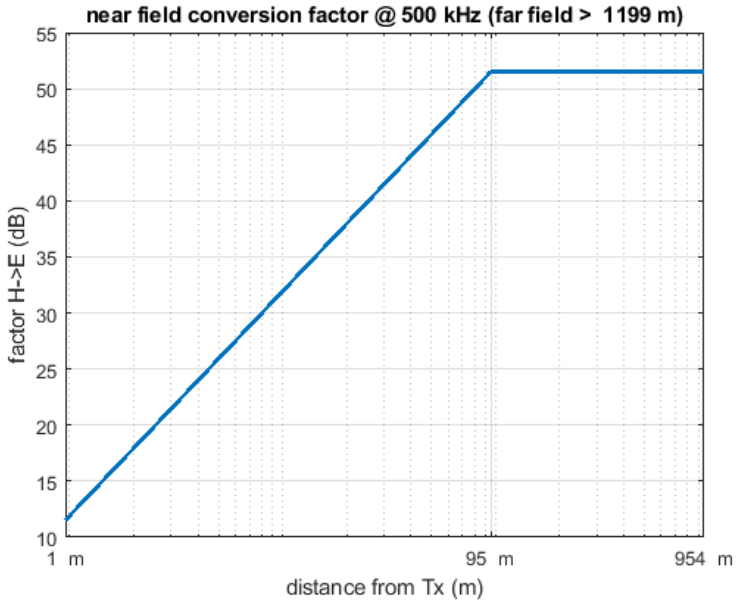


Figure 158: Near field conversion factor between magnetic and electric fields

SNRs of 10 dB and 20 dB are assumed for calculating the separation distance. Thus, 5 and 15 dBµV/m in 10 kHz are assumed to be the maximum allowed levels of interference.

Figure 159 shows the electric field. It is based on the magnetic field and the conversion was applied. For inductive loop transmitters the electric field is following a drop of 40 dB/decade in the near-field region [5]. The distances at which the interference criteria are respected are highlighted. At the minimum distance of 49 m the SNR of 10 dB is respected, at 96 m the SNR of 20 dB is respected.

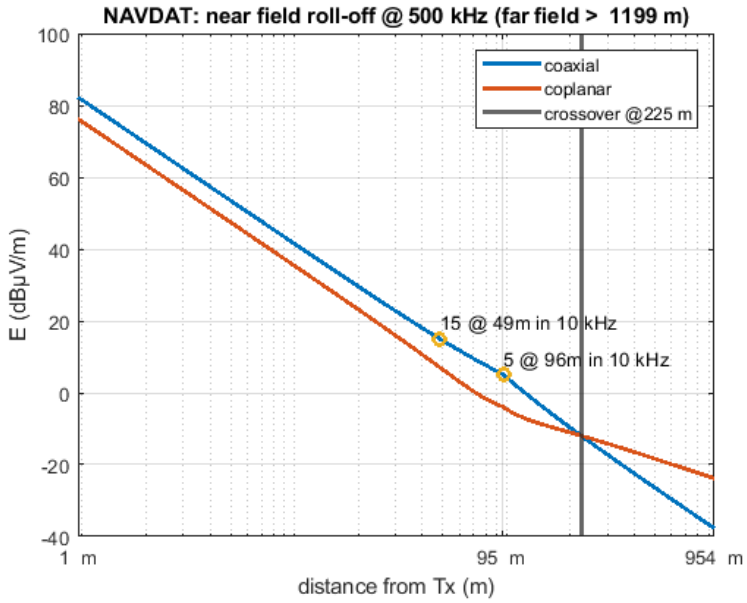


Figure 159: Roll-off function of electric ffield at 500 kHz

A5.2.4 Study between WPT and NAVTEX @ 500 kHz

According to MSC.508 (105) [43], NAVTEX systems are deployed in the frequency range 490 kHz to 518 kHz.

This study assumes unwanted emissions from WPT systems at the frequency of 500 kHz at a field strength of ~ 9.5 dBµA/m @10m in 10 kHz according to ERC Recommendation 74-01 [5].

Figure 160 shows the roll-off function of the magnetic field that is assumed in the near-field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [9]. At lower distances than 225 m the coaxial direction of the fields can be assumed as worst case. At higher distances than 225 m the coplanar direction of the fields can be assumed as worst case. The level of emissions at 10 m distance is highlighted. The near field ends at λ/2pi = 95 m. Results shown beyond this distance are not relevant for this study between WPT and NAVTEX @ 500 kHz.

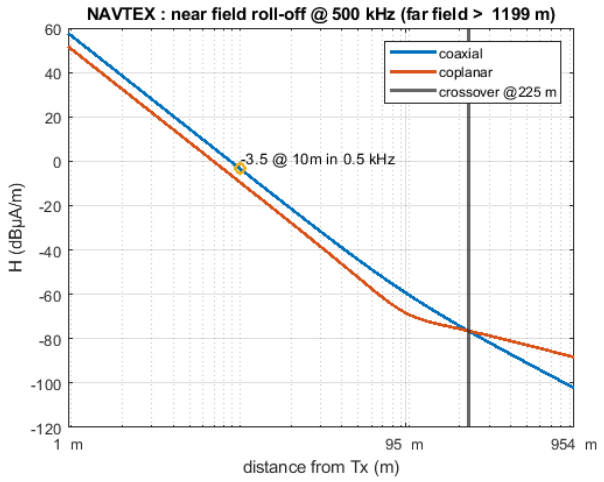


Figure 160: Roll-off function of the magnetic field at 500 kHz

According to MSC.508 (105) [43], the NAVTEX's sensitivity is given as an electric field of 2 µV/m. The bandwidth of 0.5 kHz is given in Recommendation ITU-R M.1467 [41]. In logarithmic scale this is 6 dBµV/m in 0.5 kHz.

In the near field, the impedance of a magnetic loop is low and inductive and can be approximated according to Z ~ 2370 Ω * r / λ [7], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 161. For distances above 95 m results would be applicable for H-field antennas as victim. As an example, at 50 m distance the conversion factor used would imply 4 dB less sensitive E-field antennas compared to H-field antennas with regard to H-field interference.

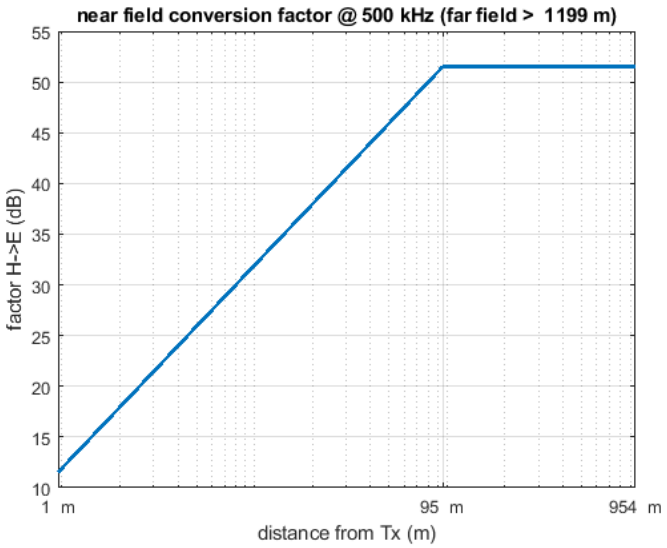


Figure 161: Near field conversion factor between magnetic and electric fields

SNRs of 10 dB and 20 dB are assumed for calculating the separation distance. Thus, -4 and -14 dBµV/m in 0.5 kHz are assumed to be the maximum allowed levels of interference.

Figure 162 shows the electric field. It is based on the magnetic field and the conversion was applied. For inductive loop transmitters the electrical field is following a drop of 40 dB/decade in the near-field region [5]. The minimum distances at which the interference criteria are respected are highlighted. At the distance of 76 m, the SNR of 10 dB is respected, at the distance of 128 m the SNR of 20 dB is respected.

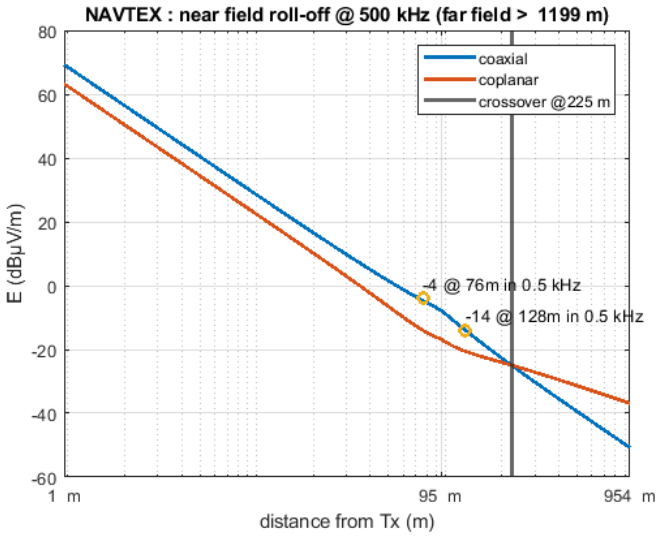


Figure 162: Roll-off function of H at 500 kHz

A5.2.5 Study between WPT-EV and MF voice @ 2182 kHz

According to MSC.512 (105) [44], MF Voice systems are deployed in the frequency range 1605 kHz to 4000 kHz.

This study assumes unwanted emissions from WPT-EV systems at the frequency of 2182 kHz at a field strength of ~ 3.1 dBµA/m @10m in 10 kHz, according to ERC Recommendation 74-01 [5]. For the receiving bandwidth of 3 kHz this value is calculated to -2.1 dBµA/m @10m in 3 kHz.

Figure 160 shows the roll-off function of the magnetic field that is assumed in the near-field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [9]. At lower distances than 51 m the coaxial direction of the fields can be assumed as worst case. At higher distances than 51 m, the coplanar direction of the fields can be assumed as worst case. The level of emissions at 10 m distance is highlighted. The near field ends at λ/2pi = 22 m. Results shown beyond this distance are not relevant for this study.

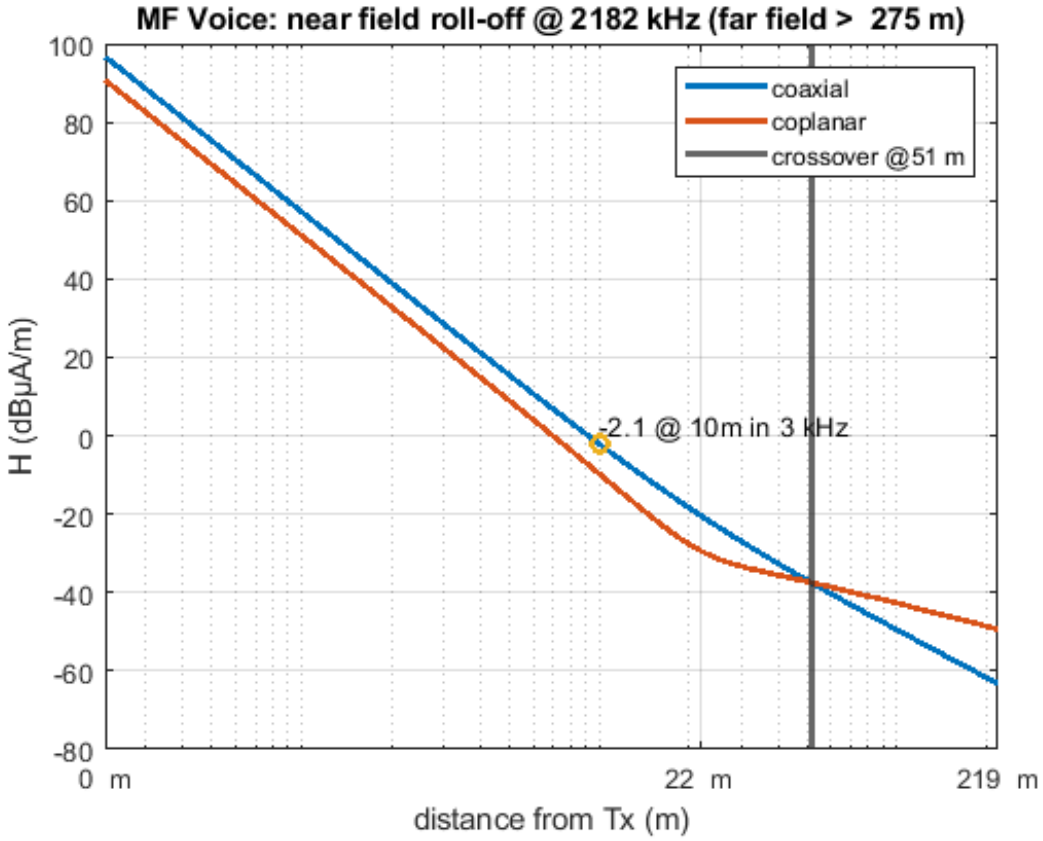


Figure 163: Roll-off function of H at 2182 kHz

According to MSC.512 (105) [44], the MF Voice's sensitivity is given as an electric field of 6 µV/m. According to Recommendation ITU-R M.1467-1 [41], the bandwidth used is 3 kHz. In logarithmic scale this is 16 dBµV/m in 3 kHz.

In the near field the impedance of a magnetic loop is low and inductive and can be approximated according to Z ~ 2370 Ω * r / λ [7], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 161. For distances above 22 m results would be applicable for H-field antennas as victim.

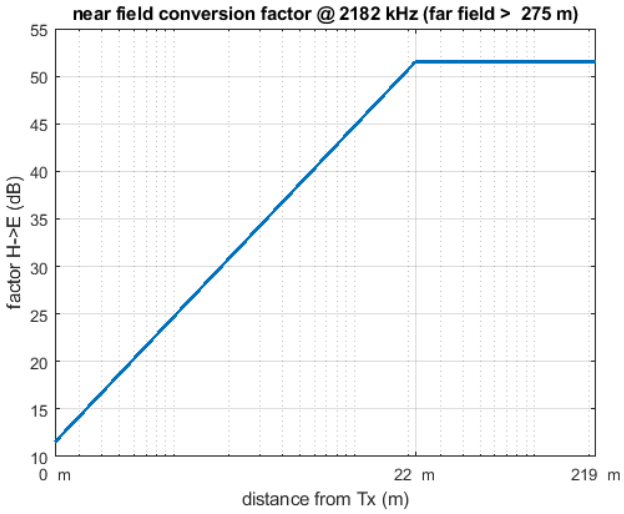


Figure 164: Near field conversion factor between magnetic and electric fields

A level of 10 dB and 20 dB below the sensitivity are assumed for calculating the separation distance. Thus, 6 and -4 dBµV/m in 3 kHz are assumed to be the maximum allowed levels of interference.

Figure 162 shows the electric field. It is based on the magnetic field and the conversion was applied. For inductive loop transmitters the electric field is following a drop of 40 dB/decade in the near-field region [5]. The distances at which the interference criteria are respected are highlighted. At the distance of 139 m the SNR of 10 dB is respected. At the distance of 446 m the SNR of 20 dB is respected. But it has to be noted that those separation distances are beyond the near field and therefore results are not valid for that range. Further assessment is needed.

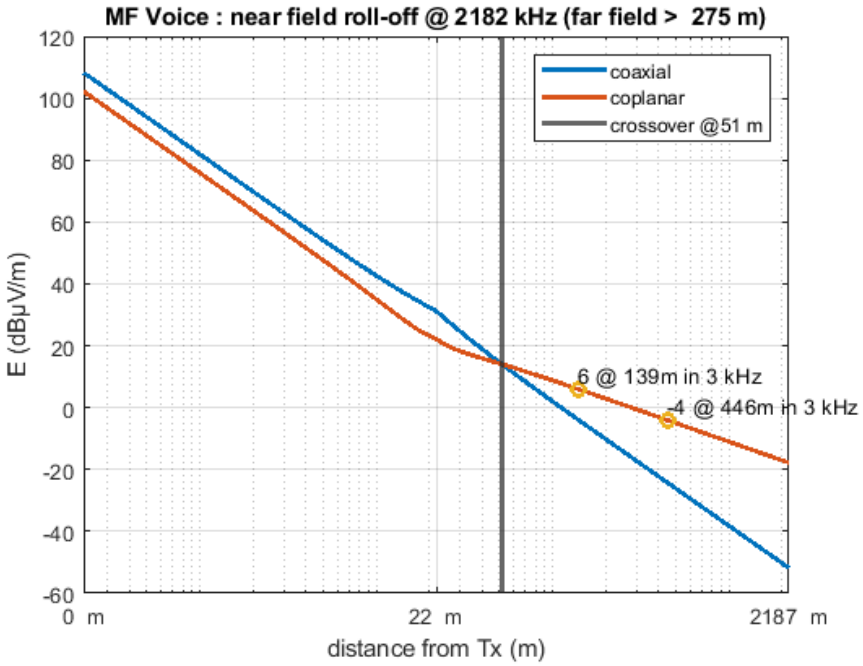


Figure 165: Roll-off function of the magnetic field at 500 kHz

A5.2.6 Typical distances between car parks and ship locks

Ship locks are areas where technical assistance like DGNSS allows the necessary level of accuracy to navigate a ship. A high accuracy is in general relevant for navigation in coastal and inland waters, as well as for auto-piloted vessels.

In order to evaluate the calculated separation distances, typical distances between car parks and ship locks were studied from satellite images. In Figure 166 and Figure 167 examples are given. The distance of 50 m is plotted there as well, which can be considered as a typical distance.

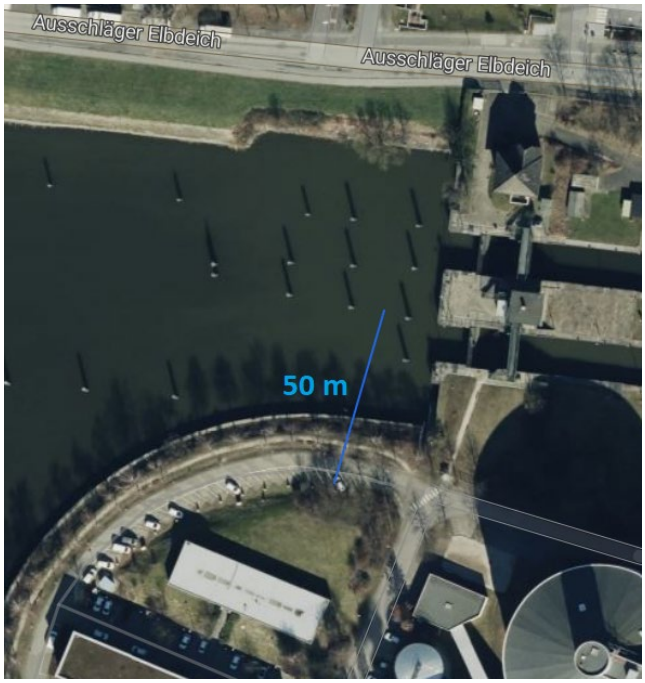


Figure 166: Distance from a company's car park to a ship lock in Hamburg, Germany (Source: Google Maps, 2025)



Figure 167: Distance from a public car park of a train station to a ship lock in Manchester, UK

A5.2.7 Summary and conclusions

Table 25 gives an overview of the results for each studied victim system. In addition to the figures shown, results based on emissions 10 dB, 20 dB and 30 dB below the limit given in ERC Recommendation 74-01 [5] are calculated.

Table 25: Study results

Victim system	Sep. distance (ERC Recommendation 74-01 [5])	Sep. distance (ERC Recommendation 74-01 [5] -10 dB)	Sep. distance (ERC Recommendation 74-01[5] -20 dB)	Sep. distance (ERC Recommendation 74-01 [5] -30 dB)
DGNSS @ 300 kHz	22 m - 34 m	12 m - 19 m	7 m - 11 m	4 m - 6 m
NAVDAT @ 500 kHz	49 m - 96 m	26 m - 49 m	15 m - 26 m	8 m - 15 m
NAVTEX @ 500 kHz	76 m - 128 m	38 m - 73 m	21 m - 28 m	12 m - 21 m
MF Voice @ 2182 kHz	139 m - 446 m (Note 1)	46 m - 139 m (Note 1)	28 m - 46 m	16 m - 28 m
Note 1: Assessment was carried out by using near field formula, and results are far field separation distances.				

The calculated separation distances based on the maximum allowed emissions of ERC Recommendation 74-01 [5] are between 22 m for DGNSS and 446 m for MF voice. They apply for maritime service receivers using E-field antennas operating at their lowest possible level of reception.

Considering electrical vehicles, examples of real world distances between car parks and ship locks can be around 50 m. According to the calculations done for E-field and H-field antennas as victim, this distance seem to protect DGNSS from interference for all studied levels of unwanted emissions, whereas for NAVDAT, NAVTEX and MF Voice a reduction of 20 dB compared to the emissions given in ERC Recommendation 74-01 would be needed.

A5.3 STUDY B: IMPACT OF "UNWANTED EMISSIONS OF WPT-EV DEVICES" ON THE MARITIME SERVICE

In this study B, the minimum separation distances between WPT charging devices and antennas of receivers operating in the maritime service allocation are calculated.

The WPT emission level is chosen to be worst-case and modelled as broadband in nature at the limits in accordance with values recommended in ERC Recommendation 74-01 [5]. Actual WPT-EV emission characteristics were not used. These values presented in the unit dBµA/m are defined for emissions within a bandwidth of 10 kHz and a distance of 10m to the emission source.

For the studies, a simplified environment without any conducting obstacles in the vicinity of the WPT charger and in the propagation path between WPT charger and victim receiver antenna is assumed. Conductive objects between the interfering source and the victim receiving antenna may influence the amplitude and orientation of the field strength vectors at the place of the receiving antenna.

The propagation model used for calculating the magnetic field strengths in these studies is identical to the propagation model presented in ERC Report 69 [9] (formulas 8,6,9 on page 7). The model according ERC Report 69 can only be used to calculate magnetic field strengths but not to calculate electric field strengths. The propagation model used in these studies calculates the magnetic and electric field strengths in near and far fields for an electrically small radiating loop antenna and is based on the classical electrodynamic laws. Because some maritime receivers may operate with electric dipole / monopole antennas and some other

maritime receivers may operate using loop antennas, both results of the propagation model, that one for electric field strength and magnetic field strength need to be considered. That model can be found in many classical textbooks on electrodynamic and antenna theory and reads as below:

$$E_\varphi = -\frac{j\omega\mu M}{4\pi}\, e^{jkr}\left(\frac{jk}{r}+\frac{1}{r^2}\right)\sin(\theta)$$

$$H_r = \frac{j\omega\mu M}{4\pi}\, e^{jkr}\left(\frac{2}{\eta r^2}+\frac{2}{j\omega\mu r^3}\right)\cos(\theta)$$

$$H_\theta = \frac{j\omega\mu M}{4\pi}\, e^{jkr}\left(\frac{j\omega\varepsilon}{r}+\frac{1}{\eta r^2}+\frac{1}{j\omega\mu r^3}\right)\sin(\theta)$$

$$k = \omega\sqrt{\mu\varepsilon}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

$$M = \pi I a^2$$

Figure 168 shows the magnetic field and electric field strengths calculated with the above mentioned propagation model for a small loop antenna carrying a magnetic moment of 1 nAm2 for the frequencies of 238 kHz, 315 kHz, 500 kHz, 1605 kHz and 4000 kHz.

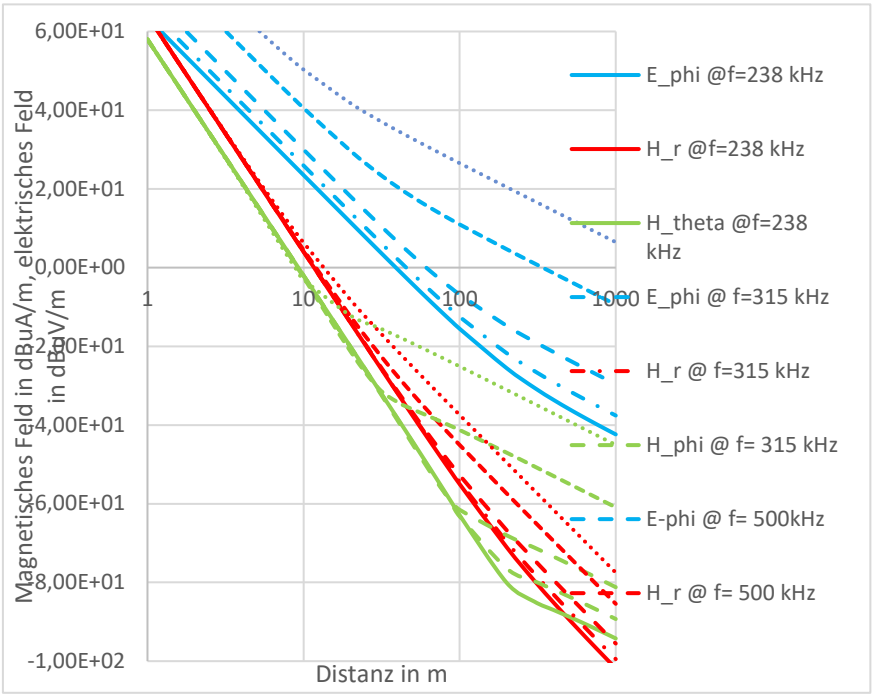


Figure 168: Field strength of an electrically small loop antenna carrying a magnetic moment of 1 nAm2

The spectrum of spurious emission signals is most likely not of white gaussian characteristic, because spurious signals do not originate from modulation artefacts. Instead, spurious emissions spectrum can often be characterised by a sum of different very narrow band signals of different frequencies. Accordingly, the spurious emission interference power is in most cases also independent of the receiver bandwidth, since usually the power of only one narrowband interference signal within the receiver bandwidth dominates the value of the interference power in the said bandwidth.

For sensitivity analysis purpose, the interference study B is based on the assumption of two different emission field strength values: -15 dBµA/m or -35 dBµA/m @ 10m distant to the interfering transmitter.

For MF/ HF interference analysis, the characteristics of the maritime receivers according to the standard ETSI EN 300 373-1 V1.4.1 [72] are considered in this study B. The minimum field strength of the wanted signal at the reception location is calculated based on the sensitivity definition according to the above mentioned ETSI standard and based on Recommendation ITU-R P.525-4, equation 8 [73]. This equation is shown below:

$$E\left(\frac{dBuV}{m}\right) = P_r(dBW) + 20\log\left(f(GHz)+\right) + 167.2$$

Accordingly, an antenna gain of the maritime receiver of – 2 dBd is assumed The results of that calculation are shown in Table 26:

Table 26: Minimum sensitivity of maritime receivers

Frequency range	Bandwidth	Sensitivity (dBµV)	Sensitivity (dBW)	E (dBµV/m)
1605 kHz	3 kHz	16	-121	-9.7
4000 kHz	3 kHz	16	-121	-1.8

The sensitivity of the MF / HF receivers defined in ETSI EN 300 373-1 [72] are based on a SINAD of 20 dB for the modulation J3E. Accordingly, a bandwidth of 3 kHz is considered. With a protection criterion I/N of -6 dB, the interference signal level should not exceed the field strength of -9.7 dB – 20 dB – 6 dB = -35.7 dBµV/m at a frequency of 1605 kHz, and -1.8 dB – 20 dB – 6 dB = -27.8 dBµV/m at a frequency of 4000 kHz should not be exceeded. It turns out, that these values are lower than the radio noise field strengths.

It should be noted that current available receivers are even more sensitive as the requirements of the standard ETSI EN 300 373-1. It can be easily recognised, that the sensitivity of the MF radio receivers does not limit the link budget of the MF maritime radio links, because the effects of radio noise dominate.

Radio noise electric and magnetic field strength are calculated according to Recommendation ITU-R P.372 [25]. The calculated field strength values are shown in Table 27. The consideration of median city man made noise may be of limited relevance, because most maritime stations are probably not operated in city environments.

Table 27 Radio Noise field strengths

Frequency range	Band-width	Radio noise magnetic field strength $H_{radionoise}$		Radio noise electric field strength E	
		Quiet receiving site	Median city man made noise	Quiet receiving site	Median city man made noise
1605 kHz	3 kHz	-62.1 dBµA/m	-41.1 dBµA/m	-10.6 dBµV/m	10.4 dBµV/m
4000 kHz	3 kHz	-65.2 dBµA/m	-43.1 dBµA/m	-13.7 dBµV/m	8.3 dBµV/m

It can be recognised, that the sensitivity of the MF radio receivers does not limit the link budget of the MF maritime radio links, because the effects of radio noise dominate. It should be noted that the above-mentioned values for maximum interference are based on the assumption, that the antenna noise figure is lower than the radio noise figure. For electrically small antennas, this assumption may not be applicable for all receiving stations and may therefore be interpreted as worst-case scenario.

However, Recommendation ITU-R M.2058 [76] defines 20 dBµV/m for the minimum usable RF field as the NAVDAT ship receiver minimum performance specifications. NAVDAT operates with 64 QAM modulation. A S/N ratio of 23 dB for 64 QAM sensitivity is quite common. Based on a protection criterion I/N = -6 dB, a maximum interference level of - 9 dBµV/m respectively -60.5 µA/m is considered in this study. This interference level may be interpreted as acceptable for best-case scenarios. Therefore, those best-case scenario consider the protection only for low performing receiving stations, because only minimum performance specifications are considered. The protection of better performing receiver stations is not considered in those best-case scenarios.

The receiver sensitivity values and corresponding protection criterions are summarised in Table 28. The relation of a protection field strength for magnetic field H_{prot} and a protection field strength for the electric field E_{prot} are interrelated by the following equation:

$$H_{prot} = \frac{E_{prot}}{377}$$

Table 28: Protection field strength levels

Frequency	Receiver Bandwidth	Sensitivity	E_{prot}	H_{prot}	Environment
1605 kHz	3 kHz	20 dBµV/m	-9 dBµV/m	-60.5 dBµA/m	No noise, minimum performance receiver
4000 kHz	3 kHz	20 dBµV/m	-9 dBµV/m	-60.5 dBµA/m	No noise, minimum performance receiver
1605 kHz	3 kHz	-9.7 dBµV/m	-16.6 dBµV/m	-68.1 dBµA/m	Quiet receiving site
4000 kHz	3 kHz	-1.8 dBµV/m	-19.7 dBµV/m	-71.2 dBµA/m	Quiet receiving site
1605 kHz	3 kHz	-9.7 dBµV/m	4.4 dBµV/m	-47.1 dBµA/m	City noise
4000 kHz	3 kHz	-1.8 dBµV/m	2.3 dBµV/m	-49.2 dBµA/m	City noise

For the evaluation of the separation distance in case of receivers equipped with magnetic or electric antennas, it is assumed that both antennas have the same efficiency and consequently the same antenna gain, because both antennas can be assumed to be electrically small.

Results of the separation distance evaluation are shown in Table 29.

Table 29 Separation distances

Receiver parameters			Separation distances			
					Worst case	
Frequency (kHz)	Bandwidth (kHz)	Receiver Antenna	WPT emission limit (dBµA/m)	Best case	Quiet receiving site	Median City man made noise
1605	3	Magnetic Electric	-35	30.7 m 19.8 m	43.2 m 35.6 m	17.1 m 10.0 m
4000	3	Magnetic Electric	-35	67 m 67 m	238 m 238 m	22.9 m 21.8 m
1605	3	Magnetic Electric	-15	104 m 104 m	263 m 263 m	41.2 m 32.2 m
4000	3	Magnetic Electric	-15	664 m 664 m	848 m 848 m	187 m 187 m

Best case results did not take into account limiting ambient noise. In quiet receiving sites no WPT-EVs are expected. Therefore, City environment results are considered as most relevant. For this scenario emissions of -15 dBµA/m would not fulfil the requirement of a maximum separation of 50 m. Emissions of -35 dBµA/m would fulfil this requirement including a margin.

ANNEX 6: TECHNICAL COMPATIBILITY STUDIES WITH RADIOCOMMUNICATIONS SERVICES USED BY NATO IN THE FREQUENCY RANGE FROM 9 KHZ TO 30 MHZ

A6.1 VLF-LF MILITARY SYSTEMS PROTECTION REQUIREMENTS FROM WPT-EV

A6.1.1 Introduction

Based on the observation that:

- The frequency ranges identified for the operation of wireless power transmission (WPT) chargers for electric vehicles (EV) are also allocated to NATO countries for radiocommunication services especially for military applications in the VLF/LF and HF range for harmonic interferences;
- Many charger types (fixed or adjustable frequency, stationary or dynamic) are considered with different powers (until 120 kW);
- The number of WPT systems will be constantly increasing (as for electric vehicles) and their distribution across the territory will not be manageable;
- No or very few studies have been conducted to assess the impact of WPT chargers on radiocommunication services in the VLF/LF and HF ranges.

The Working Group Spectrum Engineering (WG SE) would like to invite NATO to:

- Provide, to the extent possible, characteristics of systems operating in the frequency range from 9 kHz to 30 MHz (e.g. antenna and receiver characteristics, bandwidth, protection requirements and scenarios to consider)
- Participate in this activity so that the responsible project team SE24 use these characteristics to undertake compatibility studies between radiocommunication services and WPT systems.

Radiocommunication services which have allocations in the Radio Regulations (RR) [17] of the International Telecommunication Union (ITU), which are licensed and usually carefully regulated, should not suffer harmful interference from WPT-EV installations. The design and operation of WPT-EV chargers should respect this principle enshrined in RR Art. 15.12 and 15.13.

A6.1.2 Review of operating systems below 30 MHz

A6.1.2.1 VLF-LF NATO operating systems in the 9 to 150 kHz frequency range

Below 150 kHz, meteorology, radionavigation, time signals, radiocommunication for maritime mobiles and fixed services have allocations in the Radio Regulations (RR).

In the International Filing Database (BR-IFIC), approximately ~2400 frequencies are assigned to NATO countries in the 9 to 150 kHz frequency band. These assignments mainly concern mobile (RR Art. 1.24), fixed (RR Art. 1.20) transmission services, maritime (RR Art. 1.44) and aeronautical (RR Art. 1.46) radionavigation services. Land radiolocation, meteorological aids and time signals services are also present to a lesser extent. The below table lists the numbers of NATO channels assigned in the BR-IFIC (extract from July 2024).

Table 30: Channels assigned in BR-IFIC for NATO countries in the 9-150 kHz frequency range

RR Article		Radio stations and services	Number of channels
Services	Stations		
1.24	1.75	Coastal radio station (mobile maritime service transmitting station)	> 900
1.20	1.66	Fixed station (fixed service transmitting station)	> 650
1.44	1.88	Maritime radionavigation land station (land station of the maritime radionavigation service)	> 550
1.46	1.88	Aeronautical radionavigation land station (land station of the aeronautical radionavigation service)	> 100
1.48	1.89	Land radiolocation station (land station of the radiolocation service)	~ 10
1.28	1.77	Ship station (receiving station of the mobile maritime service)	~ 10
1.42	1.88	Land radionavigation station (land station of the radionavigation service)	~ 10
1.50	1.108B	Mobile station of the meteorological aids service (mobile station of the meteorological aids service)	~ 10
1.54	1.95	Station emitting standard frequencies and time signals (land station of the standard frequency and time signal service)	~ 10

The ranges 14-148.5 kHz and 255-526.5 kHz are NATO harmonised in the NJFA [53]. The public extract of the NJFA has been transposed into the ECA Table [2] (the harmonised ranges are subject to ECA36 note). NATO military fixed and mobile maritime services in these ranges cannot be ignored.

The VLF-LF fixed service (RR Art. 1.20) can be used in city, residential, rural or quiet environments for reception and/or emission capabilities. The maritime mobile services (RR Art. 1.24) are mainly used in quiet environment but can also be used near urban or residential environments, when ships are located in a harbour.

It is important to note that links established under the maritime service are also established between coastal stations with each other (RR Art. 1.75, not limited to the notion of coastline in common language but land station of the maritime mobile service) and with ship stations (RR Art. 1.77) or ship stations with each other. In addition, transportable land stations are deployed across all national territories, whether for the fixed or mobile maritime service.

The below figure shows the NATO frequencies distribution under 150 kHz.

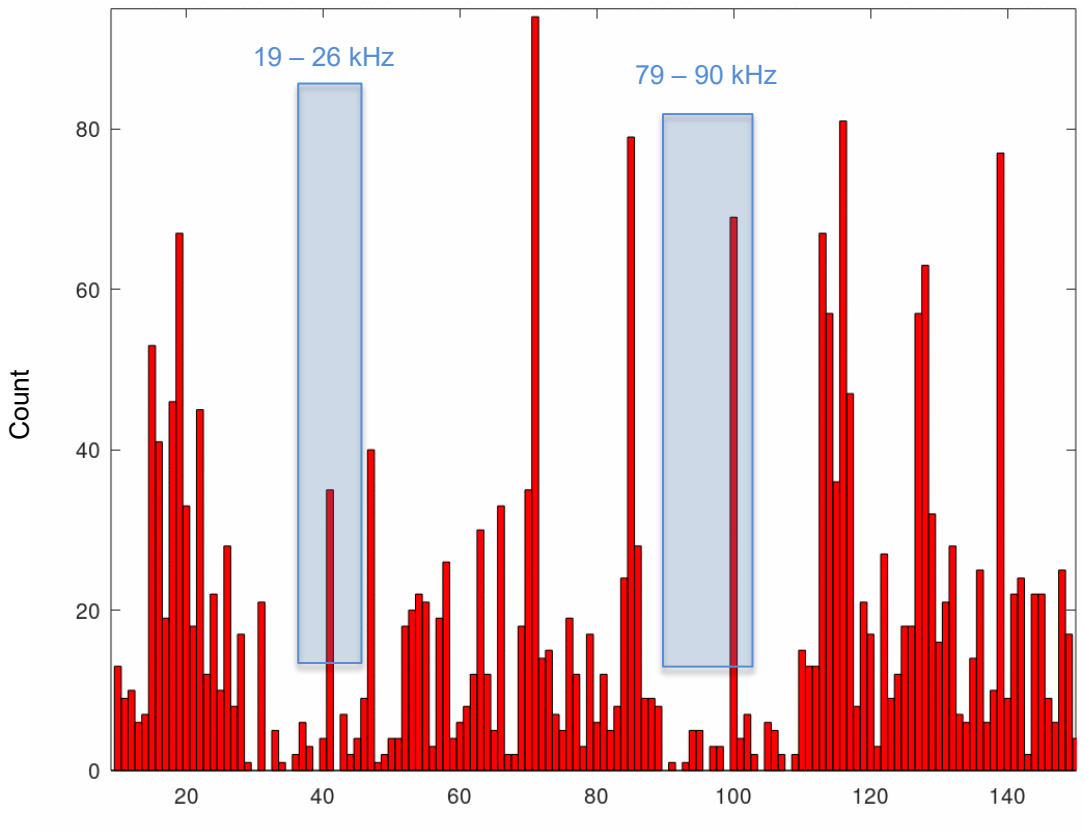


Figure 169: Count of NATO channels assigned in BR-IFIC in the 9-150 kHz frequency range

It should be noted that fundamental frequencies of WPT-EV systems are located in frequency ranges 9-25 kHz and 79-90 kHz where a significant number of NATO frequencies are assigned: ~200 for each sub-range.

- Frequency [kHz]

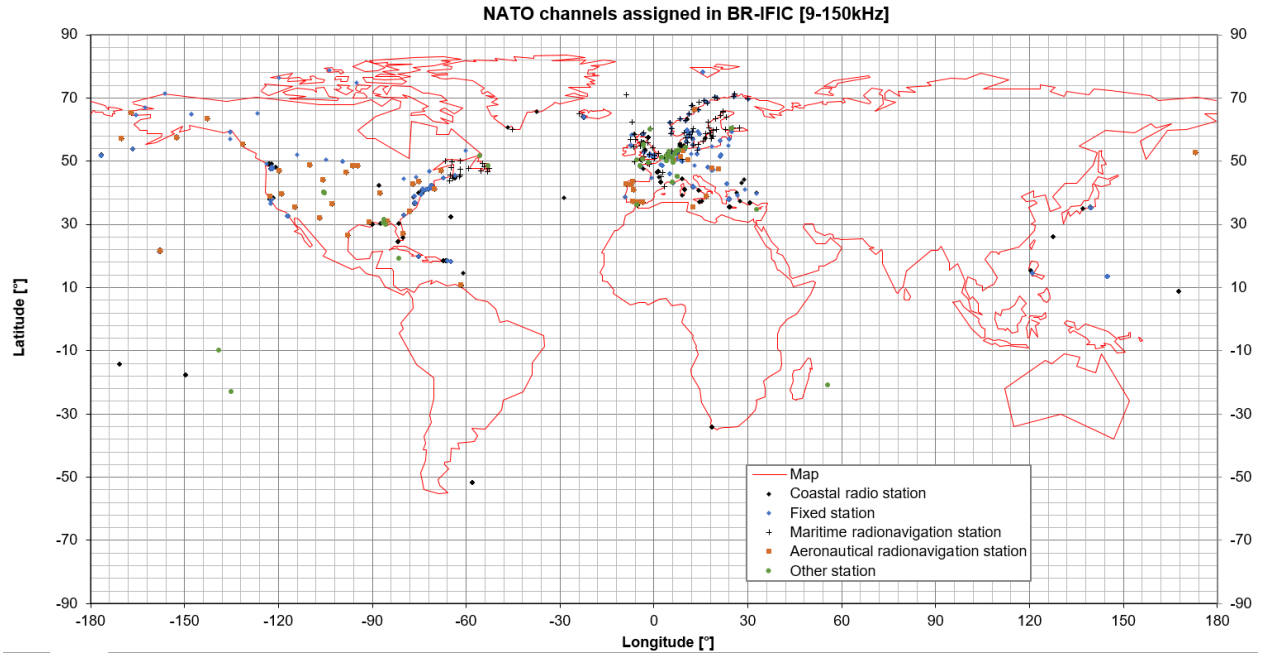


Figure 170: Geographical distribution of NATO channels

Geographically, NATO stations are mainly located in the northern hemisphere in Europe and in the United States. All types of stations can be found in coastal areas or inland.

A6.1.3 Generic characteristics for NATO radiocommunication services

In this paragraph, generic characteristics to be considered for compatibility studies with radiocommunication services are proposed.

A6.1.3.1 VLF-LF Generic characteristics

In accordance with the statements in the BR-IFIC, the operating bands allocated for each assigned frequency range from 100 Hz to 6 kHz.

Almost all statements are defined for 24/7 operating hours.

The receiving antennas used can be vertical electric whips or crossed magnetic loop antennas.

These antennas can be located in noise environments from "quiet rural" to "urban" as defined by the Recommendation ITU-R P.372 [25] and can be installed on fixed sites or mobile terrestrial and maritime stations.

Terrestrial services

To avoid interfering with fixed and mobile terrestrial services, the generic constraints to be considered are:

- For the VLF band (between 10 and 30 kHz): -25 dBµA/m (H) and 26.5 dBµV/m (E);
- For the LF band (between 30 and 100 kHz): -30 dBµA/m (H) and 21.5 dBµV/m (E).

The intrinsic characteristics of military radio communication stations cannot be distributed for confidentiality reasons. The values proposed above have been established from calculations, measurements and feedback taking into account the characteristics variability of the reception stations and a majority of geographical and local configurations.

These values establish the minimum thresholds to be respected: Some stations could have more restrictive levels due to local particularities and these values are still under review by various NATO Ministry of Defence (MoD).

Maritime services

To avoid interfering with the mobile maritime service, the limit is the atmospheric noise (value exceeded 99.5% of time) defined by Recommendation ITU-R P.372 [25] for electric and magnetic field [3]. When ships are located in a harbour, the limits are those defined for fixed and terrestrial services (see §3.1.1).

A6.1.4 Review of studies

Several organisations are involved in the standardisation and impact assessment of WPT-EV chargers with radiocommunication services operating at the same frequencies or adjacent frequencies such as ITU, International Electrotechnical Commission (IEC), European Conference of Postal and Telecommunications (CEPT) and others.

Report ITU-R SM.2451 [48] considers the impact on radiocommunication services operating below 30 MHz of radiation emanating from equipment and systems used for WPT-EV charging. This Report concludes that:

- Impact from WPT-EV to several services requires study like for fixed and maritime mobile services.

“Some studies, based on compatibility analyses assuming emissions at or near the applicable regulatory limits, indicate that WPT-EV systems could result in harmful interference to certain radiocommunication services (including broadcasting and amateur services); whereas other studies based on measurements of actual

WPT-EV systems operating in representative configurations have not identified harmful interference under the specific conditions tested."

Several aspects are still under critical review, notably how the "radiated disturbance" limits have been carried over from those limits established for a variety of ISM and SRD applications that, when originally devised, had a low chance of interfering with radio services;

The ITU-R will need to collaborate closely with the Standards Development Organisations in order to ensure that appropriate frequency ranges and technical limits are incorporated into standards as necessary to protect radiocommunication services.

In its committee draft CISPR 11 [6], published in May 2024, IEC:

- Extends the operating frequency band from 19-21 kHz (as indicated in Report SM.2110-1 [55]) to 19-26 kHz for class A and B of the WPT-EV chargers;
- Reports that WPT-EV charger Class A needs to be installed at a minimum separation distance of ~200 m and ~300 m to protect SFTS receivers from interference;
- Does not consider VLF and LF Marine communication services reducing them to the reception of submerged submarines.

In its draft addendum to ECC Report 289 [37], published in May 2024, CEPT studied the impact of WPT-EV systems working in the 79-90 kHz band. To date, this Addendum reports that the compatibility of WPT systems with some radio services, such as military and aeronautical services, has not been studied. Furthermore, scenarios of aggregated emissions from multiple WPT-EV systems have not been studied. Therefore, further studies are needed.

Also, no study evaluates the impact on monitoring systems based on the reception of VLF-LF signals to detect lighting location, ionospheric disturbances and earthquakes. Several networks of these monitoring systems are deployed worldwide like ELDN (European Lighting Detection Network) and WWLLN (World Wide Lighting Location Network) for lighting, AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) (Georgia Tech University) for ionospheric disturbances, and INFREP (International Network for Frontier Research on Earthquake Precursors) for earthquakes and others.

A6.1.5 Conclusion

Based on the generic characteristics proposed below, compatibility studies should be carried out, to assess protection distance calculation between WPT-EV chargers and terrestrial and maritime radiocommunication services.

Studies should start with impact of a stationary WPT-EV charger, then impact of the aggregation of several systems must be evaluated (different aggregation scenarios should be considered) and finally the dynamic systems must also be considered.

A6.2 **WPT-EV IMPACT ON HF MILITARY SYSTEMS**

A6.2.1 Executive summary

This section discusses the potential impact of unwanted emissions from Wireless Power Transfer (WPT) systems for Electric Vehicles (EV) on various communication services, particularly in the High Frequency (HF) range.

Impact on Communication Services

The document considers the effects of WPT-EV emissions on HF military usages under fixed service, land mobile service and maritime service. Impacts on aeronautical service is not analysed but would be worth considering.

It concludes that:

- WPT-EV perturbations at ERC Recommendation 74-01 [5] limits levels in the 1.5 MHz to 30 MHz HF band (if they were to correspond with a victim receiver frequency) could negatively impact quality of communications in military operational use cases;
- specific emission limits are necessary to avoid significant increases in man-made noise and to protect various communication services from WPT-EV interferences;
- impact depends on real WPT-EV stations power levels, control mechanisms and interferences levels;
- further studies need to be conducted to determine the aggregated impact of multiple nearby chargers, whether in operation or on standby:
- the impact of dynamic chargers, which can involve higher powers than static chargers, need to be analysed.

Military Communications

The document notes that the impact on military HF services has not been fully considered in previous studies. It references commonly used standards for HF radios like MIL-STD-461G for frequency templates and emission limits.

Noise and Interference

An analysis compares WPT-EV spurious emissions with man-made noise levels defined in Recommendation ITU-R ITU-P.372 [25]. It emphasises the need to avoid significant increases in interference levels received by military receivers in the 1.5 MHz to 30 MHz HF band to maintain the performance of HF mobile and fixed services. An approach regarding the aggregation of chargers shows that noises can reach maximum levels, on the harmonic frequencies of chargers, higher than the ambient noise levels that can be measured in an urban environment.

Compatibility Analysis

The document highlights the possible incompatibility of ERC Recommendation 74-01 spurious emission limits with military HF land mobile and fixed services. It proposes adapted emission limits for 1.5-30 MHz band to ensure compatibility with mobile and fixed service operational contexts.

Mitigation Techniques

The document suggests implementing attenuation procedures, such as filtering power supplies and controlling harmonics, to reduce the impact of WPT-EV emissions.

Protection Criteria

It discusses protection criteria for broadcast reception and suggests separation distances between WPT-EV chargers and radio receivers to comply with Recommendation ITU-R BS.1895 [69].

A6.2.2 Introduction

The increasing adoption of electric vehicles (EVs) and wireless power transfer (WPT) systems raises significant concerns about their potential impact on radiocommunication services, particularly in the very low frequency (VLF), low frequency (LF) and high frequency (HF) bands. Access to these frequency bands, particularly in NATO harmonised bands, referenced in EFIS, are crucial for military applications and other essential communication services of NATO countries.

The available WPT chargers vary in power, up to 120 kW, which could result in different emission levels and varied impacts on radiocommunication services.

To date, few studies have been conducted to assess the impact of WPT chargers on radiocommunication services in the VLF/LF and HF military bands. This gap in research makes it difficult to anticipate and mitigate potential interference. It is therefore imperative to conduct in-depth research to understand and mitigate the impacts of WPT systems on critical radiocommunication services, in order to ensure the safety and efficiency of communications in these essential frequency bands.

Radio communication services which have allocations in the Radio Regulations (RR) [14] of the International Telecommunication Union (ITU), are licensed and which are usually carefully regulated, should not suffer harmful interference from WPT-EV installations. The design and operation of WPT-EV chargers should respect this principle enshrined in RR Art. 15.12 and 15.13.

This Addendum to CEPT ECC Report 289 considers the impact of unwanted emissions from WPT(EV) systems on communications in the amateur service, the maritime service and the radio astronomy service. It concludes that the impacts of emissions related to WPT-EV in the HF range exist, but that their impact depends on power levels, control mechanisms and interference. It does not address the aggregation effect of multiple chargers operating simultaneously.

Impact of unwanted emission from WPT(EV) stations on part of the HF services (e.g. fixed services and mobile services) operated by military therefore does not appear to have been yet considered.

An analysis is made on the impact of introducing WPT with spurious emission as defined in ERC Recommendation 74-01 [5] compared to the predominant noise for HF receiver: the man-made noise level defined in Recommendation ITU-R P.372 [25].

A6.2.3 Mobile and fixed service below 30 MHz

During the last years, the HF radio medium experienced renewed interests at global level for the fixed and mobile services from the tactical, maritime and aeronautical domain. Indeed, there are significant operational interests in the capabilities provided by the latest HF technologies: IP services, faster data transmission, high resiliency and better link sustainability. Among these technologies, wideband waveforms have been standardised at NATO, including single channel wideband waveform STANAG 5069 [58] and multichannel wideband waveform STANAG 4539, annex H [59]. These technologies are being deployed within NATO nations, including many European nations. They require larger transmission bandwidths than the legacy 3 kHz single channel services to improve capabilities and to be operated efficiently. In the short term, it will increase the use of the HF frequency band and spectrum congestion.

A6.2.3.1 Military use

Lot of military applications are used under the Mobile and Fixed services below 30 MHz. It is explained by the HF systems capacities to offer services in quickly changing operational environments (material portability, very short to very long ranges, interoperability), long-distance communications without relays and low material cost compared to satellite communications systems.

Table 31 provides an example of mobile and fixed single channel frequency assignment within one country of CEPT.

Table 31: Non-exhaustive overview of one administration Armed Forces assignment, associated to mobile and fixed services

Operation	Services	Frequency band operated	Channel widths	Number of channels assigned
Air traffic control Air navigation	Mobile	3 to 30 MHz	3 kHz	> 150
Rescue	Mobile	2 to 12 MHz	3 kHz	> 50
Metropolitan network	Fixed	3 to 17 MHz	3 kHz	> 30
Mobile cooperation	Mobile	2.4 to 24 MHz	3 kHz	< 30
Training Regular exercises	Fixed, Mobile	3 to 30 MHz	3 kHz	> 300
One-off exercises	Fixed, Mobile	2 to 30 MHz	3 kHz	> 100
Trials Qualifications	Mobile	2 to 25 MHz	3 or 6 kHz	> 250
	Fixed	2 to 30 MHz (mainly 2 to 10 MHz)	3 kHz	< 110

Other allotments in the 1.5-30 MHz frequency band must be considered for specific operations, international organisations and temporary operations with other countries.

Frequency allotments are distributed over the entire HF band. This is explained by the different propagation modes used:

- Surface waves: in low relief environments (e.g. lowland and sea) where stations are close to the earth surface, this mode of radio propagation allows communication over short to medium distances. For these waves, it is preferable to transmit on frequencies from lower HF spectrum in order to reach greater distances most part the time.
- Sky waves: by small scale refractions assimilated to large scale reflections on the ionospheric layers, this mode of radio propagation allows communication over short to very long distances. For these waves, it is preferable to transmit on higher passing frequency. As received noise (e.g. man-made noise) decreases when frequency increases, operating these frequencies allows optimising the radio link budget.

Sky waves are widely used but it is the most variable mode of radio propagation. Indeed, the ionospheric propagation channel varies with solar activity, time (years, months, days) and stations location. Thus, for a given noise floor, a frequency plan distributed over the entire HF band authorises optimal radio communication at any times. This is a necessary operational criterion.

The fixed and mobile stations are used in city, residential, rural or quiet rural environments for reception and/or emission, particularly by the military stations. All types of HF fixed stations with reception capabilities are also used in these environments. The maritime mobile stations can also be used near an urban environment or residential environment, when the ships are located in a harbour.

In land forces, tactical mobile and fixed stations are designed to be quickly deployed. Tactical mobile stations are mounted on vehicles or carried by people (e.g. man pack radio). They are operated within companies or battalions and communicate with other mobile units or fixed command stations. With lower deployment constraints (installation time, material congestion, available energy), tactical fixed stations can transmit information to deployed units and military command structures in a larger radio coverage area. This is done using more efficient radio frequency materials (antennas, amplifier) than mobile stations.

Historically, real-time coordination and organisation of operation require using voice services. Nowadays, recent HF technologies offer to land forces data transfer services. Such technologies improve the

communication possibilities but requires significant link budget for an effective operational exploitation. Tactical systems are mainly operated as receivers or half-duplex transceivers.

Many fixed stations are not tactical; this means they can be maintained for decades at the same location. They are operated by all armed forces to ensure a link between deployed forces (ships, aircrafts, land forces) or other fixed stations. Those fixed stations can be located at very long distances from the receivers (> 5000 km). They also offer connectivity to military networks on a global scale and complementarity with satellite communications system, with similar services (e.g. messaging) or specific services with their proper configuration (emitter, receiver or transceiver).

Some transmission sites are distant by several kilometres from reception sites in order to limit interferences caused by very high power transmitters (> 10 kW) in co-located environments.

A6.2.3.2 Aviation use

Aeronautical HF communications (parts of the 2.850-22 MHz frequency band) provide the main long-distance air-ground communication system in areas where VHF communication is not practicable, e.g. in oceanic and remote areas, low-level overseas paths and area coverage where the area is large. Single sideband amplitude modulation voice is the modulation used. Data transmission over HF frequencies is possible and has increasing applications.

A6.2.3.3 HF NATO operating systems in the 1.5-30 MHz frequency range

In the International Filing Database (BR-IFIC), approximately ~156000 frequencies are assigned to NATO countries in the 1.5-30 MHz frequency band. These assignments mainly concern mobile (RR Art. 1.24) and fixed (RR Art. 1.20) transmission services, maritime (RR Art. 1.44) and aeronautical (RR Art. 1.46) radio navigation services. Meteorological aids and time signals services are also present to a lesser extent. The below table lists the numbers of NATO channels assigned in the BR-IFIC (extract from July 2024).

Table 32: Channels assigned in BR-IFIC for NATO countries in the 1.5 to 30 MHz frequency range

Station class	Radio stations and services	Number of channels
FX	Fixed station (fixed service transmitting station)	> 72000
MS	Ship station (receiving station of the mobile maritime service)	> 11300
FC	Coastal radio station (mobile maritime service transmitting station)	> 26900
FG	Aeronautical station (aeronautical mobile service Off-Road)	> 23500
FB	Base station (emission station of the land mobile service)	> 7600
ML	Land mobile station (reception station of the land mobile service)	> 5700
FA	Aeronautical station (emission station of the aeronautical mobile service)	> 2200
NL	Maritime radio navigation land station (land station of the maritime radio navigation service)	~ 60
SS	Station emitting standard frequencies and time signals (land station of the standard frequency and time signal service)	~ 30
SA	Mobile station of the meteorological aids service (mobile station of the meteorological aids service)	~ 20

The HF fixed service (RR Art. 1.20) can be used in city, residential, rural or quiet environments for reception and/or emission capabilities. The maritime mobile services (RR Art. 1.24) are mainly used in quiet environment but can also be used near urban or residential environments, when ships are located in a harbour.

It is important to note that links established under the maritime service are also established between coastal stations (RR Art. 1.75, not limited to the notion of coastline in common language but land station of the maritime mobile service) and ship stations (RR Art. 1.77) or ship stations with each other.

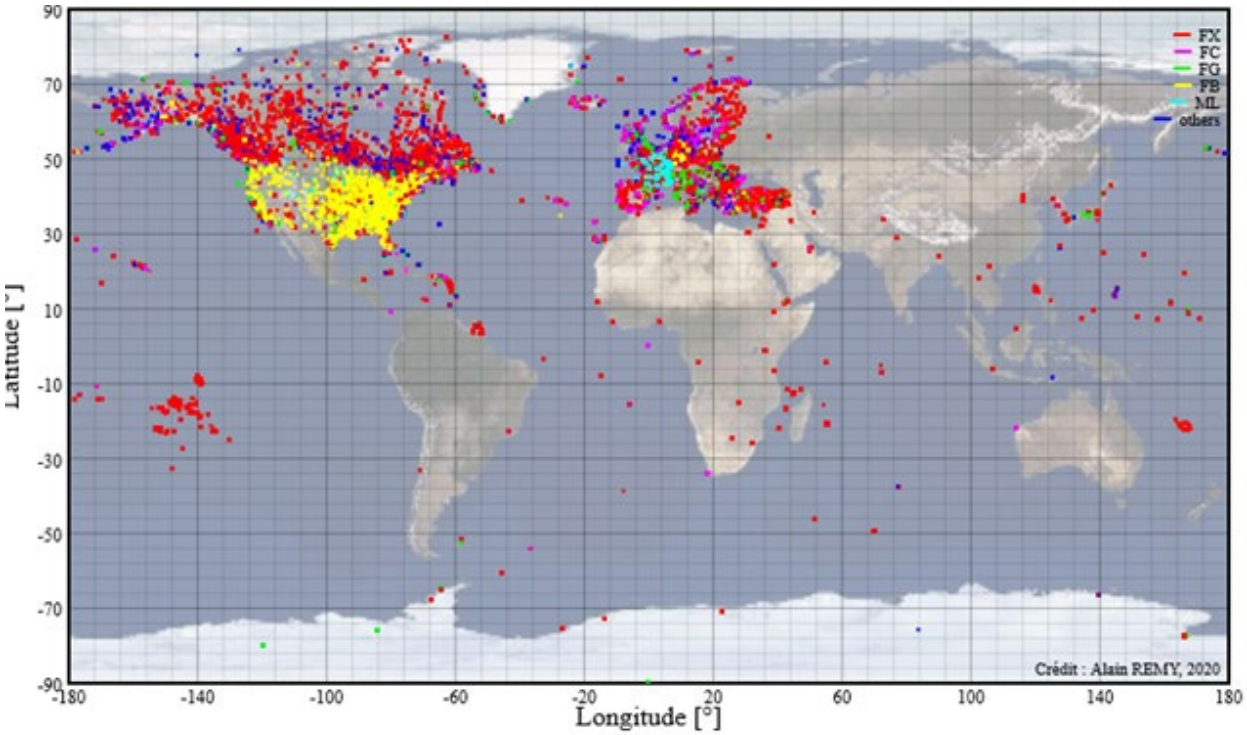


Figure 171: Geographical distribution of HF NATO channels, 2024/06 data (colours from Table 32)

Geographically, NATO stations are mainly located in the northern hemisphere in Europe and in the United States. All types of stations can be found in coastal areas or inland.

Stations can sometimes be used to relay signals, which highlights the importance of avoiding disturbances near receiving antennas.

However, the list of declared channels is not exhaustive. Some nations may declare reserve channels that are not used all the time, while it is possible that tactical stations are not declared here. Temporary frequency assignments also do not appear to be mentioned.

A6.2.3.4 Results of studies from scientific community

The Report ITU-R SM.2451 [48] summarises studies analysing potential interference caused by harmonics of WPT-EV in amateur radio, broadcasting and aeronautical bands. These include laboratory measurements, simulations and field tests.

Report ITU-R SM.2451 states that “most of the operating ranges for WPT systems are not co-incident with any broadcasting band and so radiation at these operating frequencies are unlikely themselves to cause harmful interference to broadcasting services. However, it is possible that radiation on harmonically related frequencies could lie within the LF (148.5 kHz to 283.5 kHz) MF (526.5 to 1606.5 kHz) or HF (several between 3.2 MHz and 26.1 MHz) broadcasting bands.” This means that military VLF-LF bands (3 kHz-300 kHz) have not always been properly taken into account.

Several studies are cited, some of which are reproduced here. The study conducted in the United States by radio amateurs did not find any significant impact but harmonics of the signal are visible at 10 meters. The study was conducted in different environments across the country. It shows that reception on a frequency corresponding to a harmonic of the WPT-EV charger remains possible but reduces the quality of the signal-to-ambient-noise-peak ratio, possibly because the charger harmonic adds inconsistently to a level of artificial noise.

The study conducted in Japan found that levels are generally integrated into ambient noise levels. However, a minimum protection distance of 5 m is determined to avoid interfering with certain railway systems. For critical applications, a distance of 30 to 50 meters is suggested between an HF antenna and a WPT-EV charger.

The study conducted by China concludes that in highly noisy areas, no significant interference was detected. However, in rural and suburban areas, larger separation distances are necessary. Unfortunately, the test conditions used for the study are quite different from the reception conditions assumed in the ITU-R Recommendations and this study, as the others, do not address the aggregation of chargers.

In these studies, harmonics are the main sources of interference: 2nd and 3rd in the LF (148-283 kHz) and MF (525-1705 kHz) bands. Harmonics of order 6 to 21 can affect HF communications. At distances of 10 meters, some values were above the acceptable thresholds in HF, resulting in sensitivity losses. These disturbances do not necessarily come directly from the inductive loops themselves, but also from electrical power sources.

These studies emphasise the need to implement attenuation procedures (filtering of power supplies and chargers, harmonic control), some of which are mentioned in paragraph §3 "POSSIBLE MITIGATION TECHNIQUES TO REDUCE THE IMPACT OF WPT-EV UNWANTED EMISSIONS" of the Draft Addendum to ECC Report 289.

Finally, ANNEX 8: describes analyses based on the protection criteria for AM broadcast reception and on possible separation distances between WPT-EV chargers and radio receiver.

This study suggests that, “to comply with Recommendation ITU-R BT.1895 [69] (Protection criteria for terrestrial broadcasting systems), the contribution from an interferer without status in the ITU Radio Regulations [14] must be 20 dB below the receiving system noise; this gives the following limits:

- – Band 5 (LF): (22.0 – 20.0) = −42.0 dBµA/m;
- – Band 6 (MF): (28.0 – 20.0) = −48.0 dBµA/m;
- – Band 7 (HF): (−48.0 – 20.0) = −68.0 dBµA/m.

The document provides two tables (A8-1 and A8-2) for limits on WPT-EV radiated emissions to protect radio communication services operating below 30 MHz where the WPT-EV system is not locked to the broadcasting raster, and when WPT-EV system is locked to the broadcasting raster.

This ITU summary concludes: “The studies indicate that the operation of WPT-EV in the 19-21 kHz, 55-65 kHz and 79-90 kHz frequency bands […] require tight control of the radiation from WPT-EV systems to make it compatible with radio communication services with allocations in other frequency bands particularly in harmonically related bands.

In the studies, concern was identified about the impact of radiation from WPT-EV systems on the broadcasting service and the amateur service. Some studies show that the current emission limits for WPT-EV systems could result in harmful interference to these radio communication services.”

ECC Report 289 [37] recalls that there are different (3) types of charger frequency behaviour:

- Searching and choosing the operating frequency for best efficiency;
- Dedicated discrete operating frequencies;
- Fixed operating frequency.

The potential impact of harmonics is therefore even more difficult to estimate.

One study in this document points that: “It will be seen that at 5 MHz, the emissions exceed the rural background noise at distances of up to 1.5 km from the WPT installation and at 10 MHz this distance increases to 2.0 km. This gives added weight to the argument that spurious emissions measured at 10 m need to be very significantly below the current limits to prevent harmful interference to radio services.”

It remains to be demonstrated, through measurements on real systems ready to be industrialised, what is the impact distance of harmonics on the HF band.

A6.2.3.5 Impact of unwanted emissions from WPT-EV stations on the fixed and mobile service in the military HF band

Considering the future density of wireless power transmission (WPT) systems and their potential proximity with the HF mobile and fixed stations used in their operational use context, it is necessary to fix the unwanted WPT emissions at levels bringing no significant additional interferences to the HF receiving stations. So that their impact on the HF reception quality (HF radio coverage) would be limited.

A6.2.3.6 HF current man-made interferences

The radiofrequency noise picked up by the receiver antennas has a big impact on the quality reception and thus on the radio links performances as the radio coverage. In the HF frequency band (1.5-30 MHz), the most powerful constantly present noise picked by the receiver is the man-made noise.

This noise level as defined in Recommendation ITU-R P.372 [25] corresponds to the aggregated unintended radiations from electrical machinery, electrical and electronic equipment, power transmission lines, or from internal combustion engine ignition. This noise is higher than the HF reception chains self-noise and constitutes a background noise.

In the latter recommendation, the median man-made noise is characterised by a noise factor for different environments. The noise in city environment is the most powerful man-made noise and this encountered in quiet rural environment is the lowest.

The relation between the noise factor and the electrical field is given in this recommendation. Assuming the well-known relation between electrical field and magnetic field verified ($\frac{E}{H} = 377\ \Omega$), the level of magnetic field corresponding to the median man-made noise is described in the below figure.

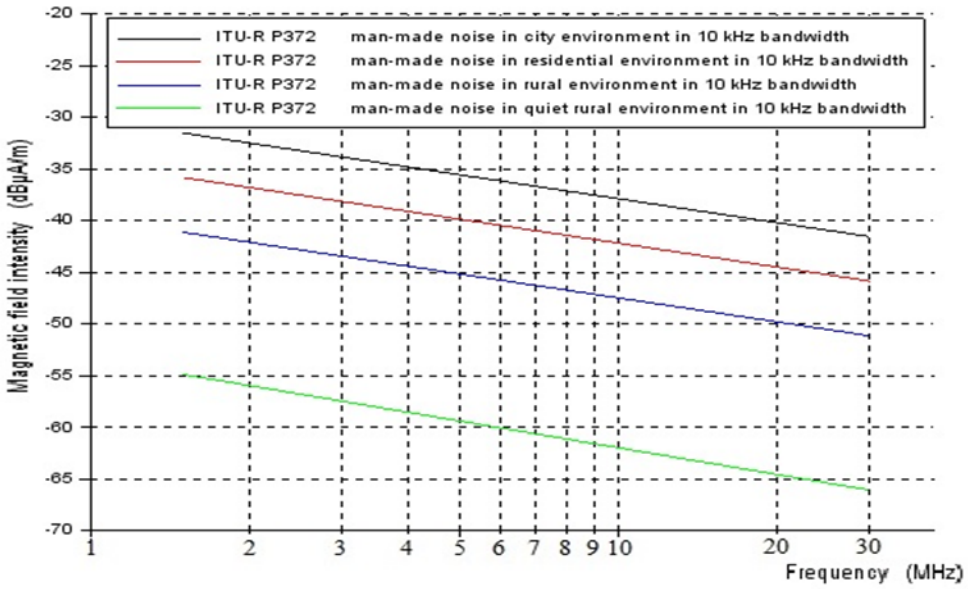


Figure 172: Magnetic field corresponding to Recommendation ITU-R P.372 [25] median man-made noises in 10 kHz receive bandwidth, versus frequency

These curves are median values. There are variations of the curve according to the location of the station and the time characterised in this recommendation for city, residential and rural environments. Deviation values are not given for a quiet rural environment.

Table 33: Values of decile deviations of man-made noise from the Recommendation ITU-R P.372, table 2 [25]

Category	Decile	Variation with time (dB)	Variation with location (dB)
City	Upper Lower	11.0 6.7	8.4 8.4
Residential	Upper Lower	10.6 5.3	5.8 5.8
Rural	Upper Lower	9.2 4.6	6.8 6.8

A6.2.3.7 HF military internal receiver noise floor

Receiver components generate internal noise in the receiving chain. Origin of this noise is multiple.

Johnson-Nyquist noise, also called as "thermal noise", is a main component of this noise. This electronic noise is generated by the thermal disorder movement agitation of the charge carriers (e.g. electrons) inside an electrical conductor at thermal equilibrium, regardless the applied voltage. The noise level increases with increasing temperature.

This noise has a nearly Gaussian amplitude distribution, this named Gaussian noise. For a finite bandwidth, such as radio bandwidth operated in radio communications, this thermal noise is approximately white, meaning that its power spectral density is nearly constant in this bandwidth. Thus, for radio transmission this noise is considered white and takes a form close to a noise floor for the receiver in the HF radio band.

Others noises sources specific to the receiver chain could have an impact on the internal noise observed in reception. One of these is quantisation noise. It can be observed in digital reception chains with analogue to digital converters integrated in the chain.

For military receivers, section 5.4.1.7 "Receiver sensitivity" in MIL-STD 188-141 Revision D [81] specifies a sensitivity value to be respected. The maximum receiver noise floor authorised by this standard can be estimated from this characteristic.

The less restrictive sensitivity value to respect for HF receivers required by MIL-STD 188-141 Revision D [81] is -111 dBm for an unmodulated signal in a 3 kHz single sideband mode, producing an audio output with a SINAD of at least 10 dB over the operating frequency range.

Thus, a minimum receiver internal noise floor can be estimated 10 dB under this value, leading to a -121 dBm in a 3 kHz bandwidth noise floor, written -121 dBm/3 kHz.

This value may be arbitrarily extrapolated to an E field and H field value (within a 10 kHz bandwidth to have a basis for comparison with current standards).

The following section shows that these performance levels are often better than the average ambient noise that can be received by an HF antenna.

A6.2.3.8 Preeminent noise floor for military receivers

Section A6.2.3.6 describes the noise floor picked up by receiving antenna. Section A6.2.3.7 indicates the maximum noise floor produced within the military receiver circuits.

Receiving antennas operated on military Mobile stations and military Fixed stations usually have significant sufficient height characteristics. The greater the effective height, the more the field received is converted to a higher electric signal by the receiving antenna.

Large tuned or broadband antennas are generally operated on fixed stations. On mobile stations, magnetic or electric tuned transmitting antennas are commonly used for emission and reception. For both military Mobile and Fixed stations, small magnetic and electric active antennas with preamplifier are also operated for reception only.

Thus, for HF military receivers, the man-made noise received by the antenna in the military HF band is commonly assumed to be the predominant noise at the reception, with electrical levels above receiver internal noise floor. Local radio noise received therefore largely determines the quality of reception.

The below figure presents the minimum receiver internal noise floor extrapolated to a value in a 10 kHz bandwidth (calculation proposition in annex), the different man-made noise levels according to Recommendation ITU-R P.372 [25] and an HF measurement in city environment with a low profile antenna used on surface ships. The real noise equals the man-made medium theoretical noise in city environment for 30 MHz.

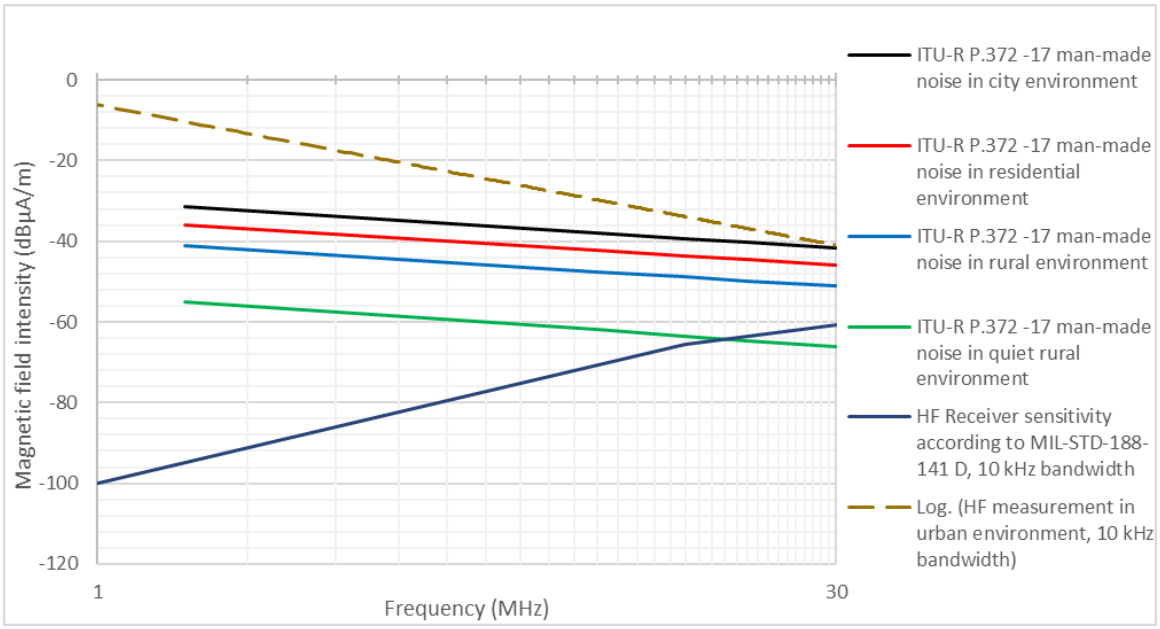


Figure 173: Magnetic field corresponding to Recommendation ITU-R P.372 [25] median man-made noises in 10 kHz receive bandwidth, HF receiver minimal sensitivity and an example of HF measurement, versus frequency

This figure shows that HF receiver can achieve better sensitivity signals than man-made noise, but that antenna may acquire higher noise signal. Preliminary, the antenna has been tested in a Faraday cage environment, showing a medium sensitivity of -45 dBµA/m on the HF spectrum.

The log. extrapolation of the HF measurement contains useful signals and environment noise. It means that an interferer, such as a WPT-EV, could increase the noise floor and prevent or decrease the reception quality of far and low levels signals.

In this analysis, to evaluate the WPT(EV) unwanted emissions impacts on HF operational link in reception, ERC Recommendation 74-01 spurious limits proposed for HF band are compared to Recommendation ITU-

P.372 [25] man-made noise levels in possible military operational scenarios where receivers would be operated in the vicinity of the WPT(EV) stations. This approach has the advantage of being generic by comparing levels directly in the $dB\mu A/m$ unit of WPT(EV) magnetic field limits proposed for unwanted emission at 10 meters. Thus, these levels are unbiased by a unit conversion of these values.

Moreover, if the ERC Recommendation 74-01 levels were compared to the internal receiver noise level to evaluate to the impact on the reception quality, the approach would not be generic. Indeed, it would require considering a representative panel of antennas and reception chains to compare level, bringing bias and complexity on the analysis. Furthermore, this would not be valid because the man-made noise received is considered predominant for a large part of HF military receiving stations.

An article [78] from the Dept. of Robust Radio Communications of the FOI Swedish Defence Research Agency also considered these levels as limiting factors for HF radio receivers and compared WPT(EV). In this article, authors evaluate the distances to avoid WPT(EV) unwanted emissions impacts from a WPT(EV) system on HF receivers. WPT(EV) levels where measured on a WPT(EV) implementation. They evaluated a 400 m to 2.8 km distance for the 3-30 MHz band in a Recommendation ITU-R P.372 [25] rural environment to avoid degradation of receiver sensitivity.

A6.2.3.9 Comparison between ERC Recommendation 74-01 spurious limits and Recommendation ITU-R P.372 man-made noise levels

WPT stations will generate electromagnetic waves whose energy is mainly contained in their operating band. However, a part of the energy emitted overflows this band. For the unwanted emissions in the 1.5-30 MHz, the following comparison can be made between ERC Recommendation 74-01 and Recommendation ITU-R P.372 [25] man-made noise levels.

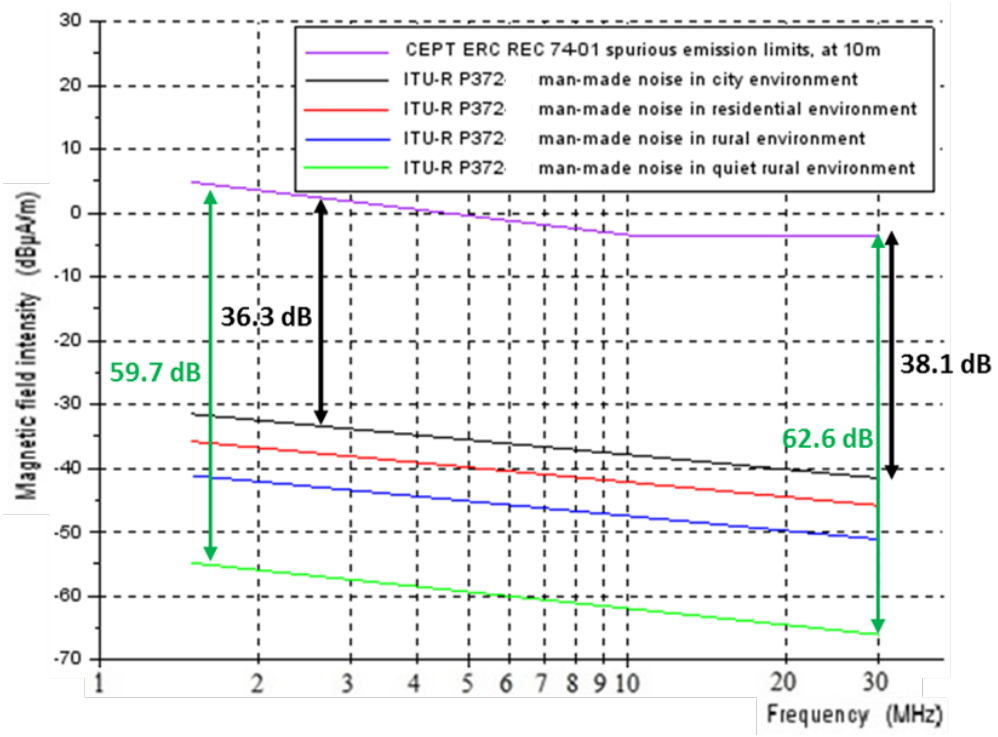


Figure 174: ERC Recommendation 74-01 spurious emission limits at 10 m in 10 kHz bandwidth compared to Recommendation ITU-R P.372 [25] median man-made noise curves in 10 kHz bandwidths

In order to avoid sharp losses in HF mobile and fixed services links performances, it is necessary to avoid significant rise in interferences picked up by antennas of HF mobile and fixed stations used in their operational use contexts. Thus, it is necessary to avoid WPT spurious emissions limits allowing significant increase in the man-made noise perturbations picked-up by these stations.

A6.2.3.10 Attenuation to apply at distances different from 10 meters

ERC Recommendation 74-01 [5] spurious emission limits at 10m are the limits proposed in the section 3.2 Applications and use cases. In order to estimate the magnetic field level for the range from 1.5 MHz to 30 MHz at different distances, attenuation conversion factors must be applied to these limits. Attenuation values vary with the regions of the electromagnetic field considered, such as near and far fields. Thus, for a fixed distance, its value varies with the wavelength of the radiated signal.

For the 1.5-30 MHz HF band, the radiated element of the systems described in section 3 System characteristics of WPT Applications is electrically small. Thus, considering λ the wavelength of the radiated signal, the following regions could be defined:

- the reactive near-field region where the magnetic field level falls off as $\frac{1}{r^3}$, equivalent to a 60 dB/decade decay rate. This region is defined for distances well below $\frac{\lambda}{2\pi}$ from the radiating element;
- the far-field region where the magnetic field strength falls off as $\frac{1}{r}$, equivalent to a 20 dB/decade decay rate. In the literature, for electrically small antennas, this region is defined for distances higher to 3. λ from the radiating element;
- the transition zone including the radiative near-field region. This zone is defined for distances between a value well below $\frac{\lambda}{2\pi}$ and 3.λ from the radiating element. In this region, the magnetic field attenuation to consider is not clearly defined. The decay rate remains smaller than for the reactive near-field region: inferior to 60 dB/decade.

Conversion factors C30m & C3m versus frequency curves from ETSI EN 300 330, annex I [68] confirm these boundaries and decay rates.
In this study B, these factors will be applied. For distances not equal to 30 m or 3 m, hypothetical conversion factors will be estimated from these curves.

Effect of WPT-EV transmitting near a fixed or mobile station on the noise rise in city and residential environments

In order to evaluate the WPT spurious emissions at ERC Recommendation 74-01 [5] limits received by HF stations, in city and residential operational use conditions, scenarios are evaluated:

- for a mobile station: a 5 meters' minimum distance in city environment and a 10 meters' minimum distance in residential environment;
- for a fixed station: a 10 meters' minimum distance in city and residential environments.

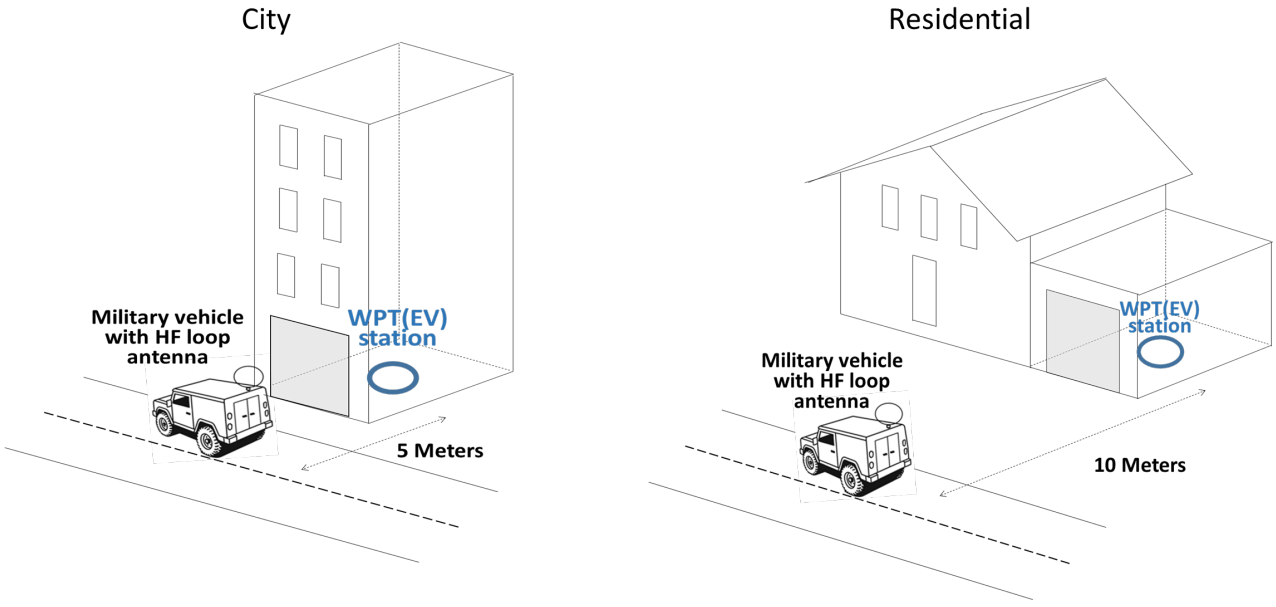


Figure 175: City and Residential scenario for a mobile station

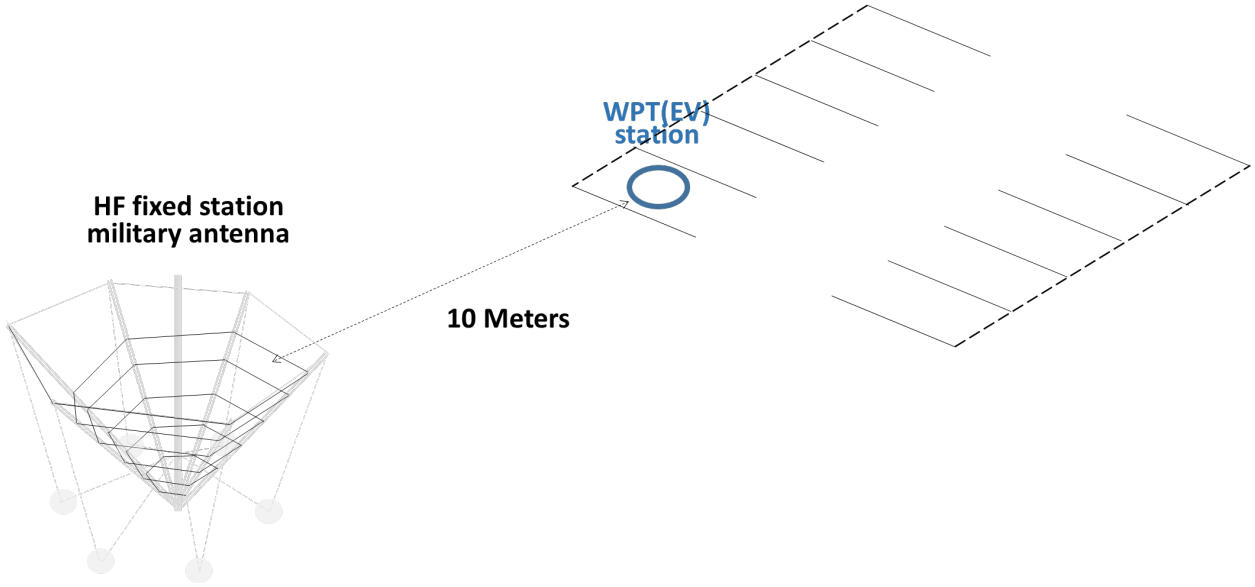


Figure 176: City and Residential scenario for a fixed station

At 5 meters, in the 1.5-30 MHz HF band, a hypothetical 5 meters conversion curve can be considered following the same shape as the C3m conversion factor versus frequency curve at 3 meters, from ETSI EN 300 330 Annex I. This curve takes the near field to far-field attenuation and its variations with wavelength into account. Thus, at 5 meters, the ERC Recommendation 74-01 limits would increase by approximately 17.8 dB at 1.5 MHz to 7 dB at 30 MHz.

If Recommendation ITU-R P.372 [25] is considered 17 median man-made noise values as the current perturbations picked-up by these HF mobile or fixed stations and only one WPT station, the WPT emissions would increase the median man-made noise by:

- Approximately 54 dB at 1.5 MHz to 45 dB at 30 MHz, in city environment at 5 meters;
- 36.3 dB at 1.5 MHz to 38.1 dB at 30 MHz, in city environment at 10 meters;
- 40.6 dB at 1.5 MHz to 42.4 dB at 30 MHz, in residential environment at 10 meters.

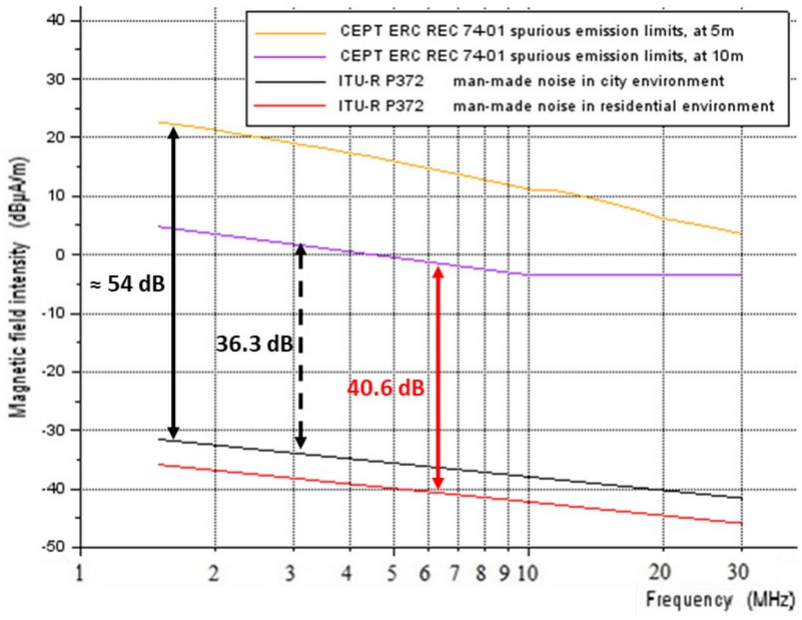


Figure 177: ERC Recommendation 74-01 [5] spurious emission limits estimated at 5 & 10 meters in 10 kHz bandwidths compared to Recommendation ITU-R P.372 [25] median man-made noise curves in 10 kHz bandwidths

Effect of WPT-EV transmitting near fixed or mobile station on the noise rise in rural environments

In order to evaluate the WPT spurious emissions at ERC Recommendation 74-01 limits, in these rural operational use conditions, between a HF station and a WPT station in a parking lot or a domestic garage, a 30 meters' minimum distance in rural environment can be estimated.

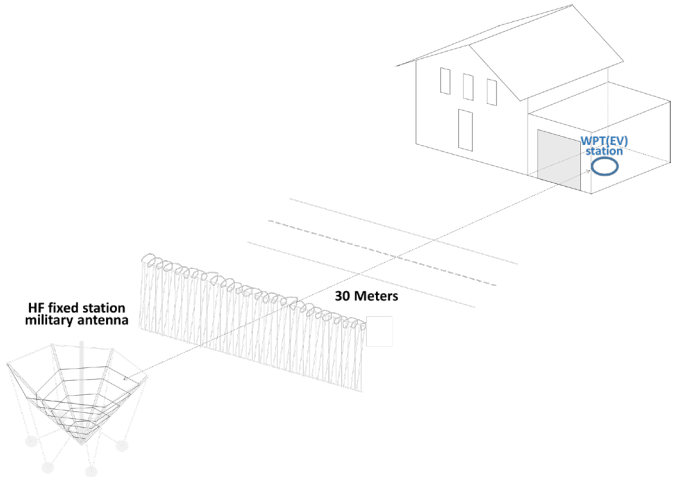


Figure 178: Rural scenario for a fixed station

At 30 meters' distance, on the 1.5 MHz to 30 MHz HF band, we consider the C30m conversion factor versus frequency curve at 30m from the standard ETSI EN 300 330, annex I [68]. This curve takes the near field to far-field attenuation effect and variation with wavelength into account.

Thus, at 30 meters, the ERC Recommendation 74-01 limits would decrease by 26.5 dB at 1.5 MHz to 9.5 dB at 30 MHz.

If Recommendation ITU-R P.372 [25] is considered median man-made noise values as the current perturbations picked-up by these HF mobile or fixed stations and only one WPT station, the WPT emissions would increase the median man-made noise by 19.4 dB at 1.5 MHz to 38.2 dB at 30 MHz, in rural environment at 30 meters.

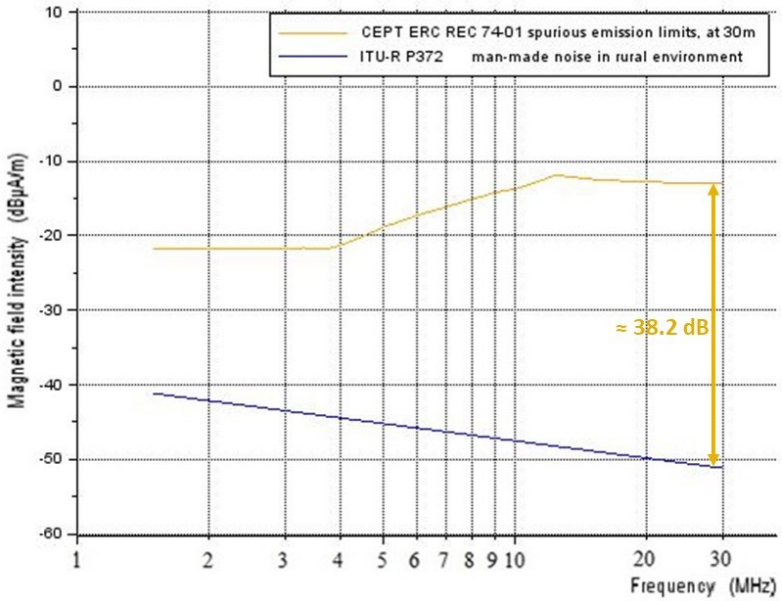


Figure 179: ERC Recommendation 74-01 spurious emission limits estimated at 50 meters in 10 kHz bandwidth compared to Recommendation ITU-R P.372 [25] median man-made noise curve in 10 kHz bandwidth

A6.2.3.11 Conclusion of unwanted emission perturbation from a single WPT-EV station on the mobile and fixed service receiver in HF military frequency band

This compatibility analysis highlights the incompatibility of ERC Recommendation 74-01 [5] spurious emission limits with HF mobile and fixed stations use in their operational contexts. It has been shown that if applying ERC Recommendation 74-01 [5] spurious emission limits, the man-made noise will increase by 36 dB or higher than average HF man-made noise identified in Recommendation ITU-R P.372 for the HF frequency band.

A6.2.4 Complementary analysis on protection distances

The theoretical approach above describes situations where a military HF receiver is at 5 meters, 10 meters and 30 meters from a WPT-EV charging station and shows interference levels ~50 dB too high compared to the median ITU noise levels.

In the HF band (2 to 30 MHz), the harmonics generated by WPT-EVs will propagate beyond 10 meters following the curves given in the document "Propagation model and interference range calculation, for Inductive Systems 10 kHz - 30 MHz" ([9], figure 9).

It shows that at 100 meters an attenuation of 27 dB is provided compared to that observed at 10 meters for the example of a harmonic at 4.775 MHz.

If there is interference of 50 dB at 10 meters, it will still be 23 dB at 100 meters.

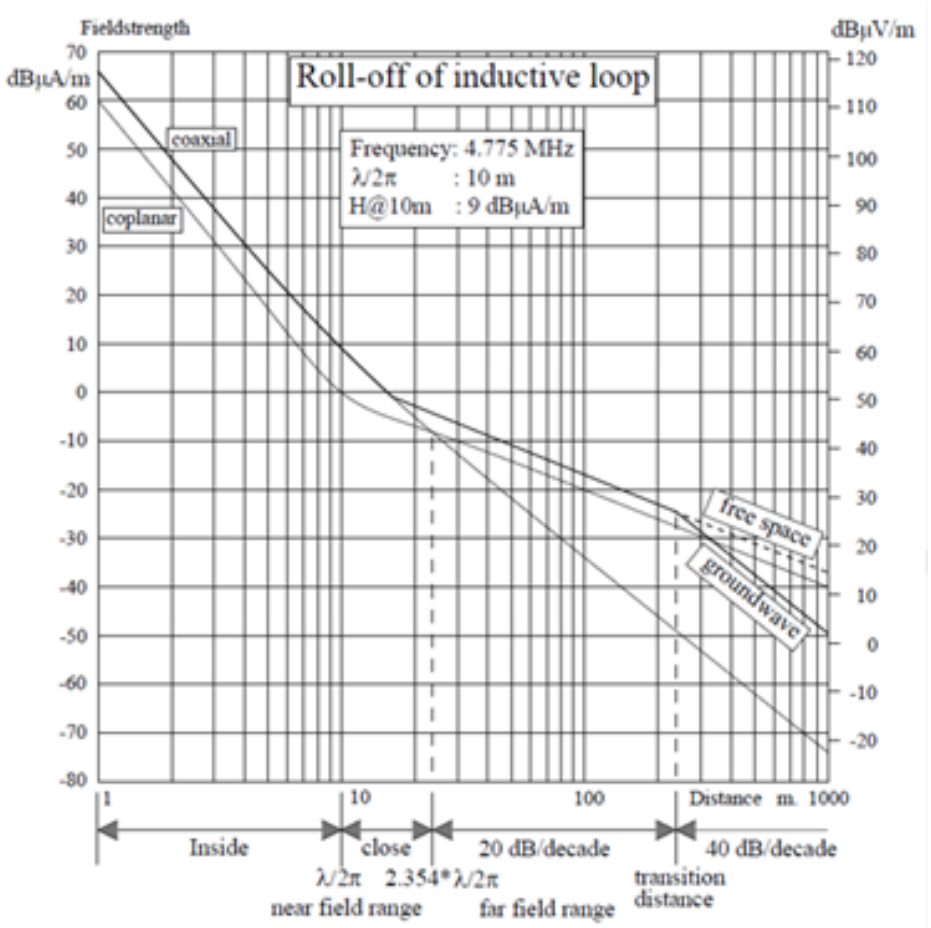


Figure 180: Roll-of inductive loop field strength decrease

If a greater distance is considered, in ground wave, it takes 600 m for an attenuation of 50 dB, bringing the interference at 4.775 MHz to the same level as the radio electric noises proposed by the ITU.

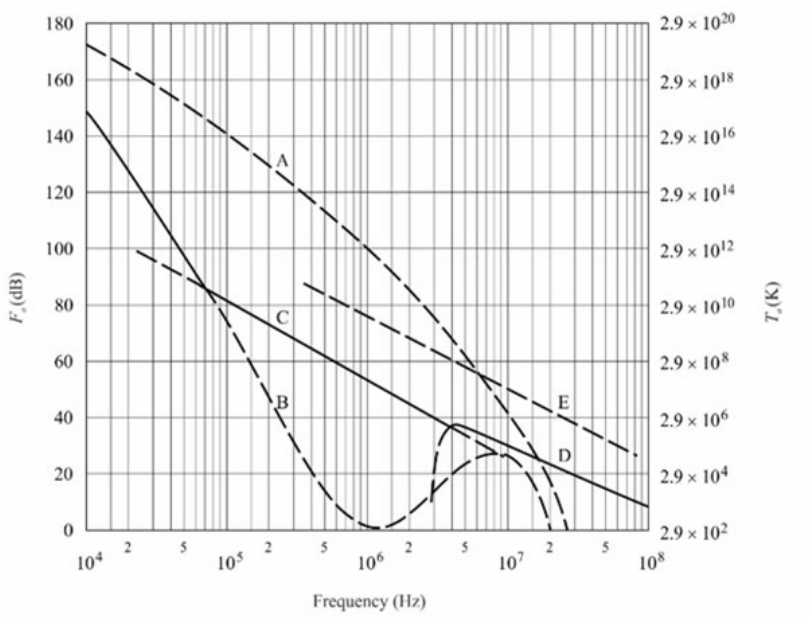


Figure 181: Artificial noise factor (Fa) versus frequency, Recommendation ITU-R P.372 [25]

The distances required between WPT-EV stations that would respect the harmonic disturbance levels defined by the standards and military receivers may depend on the frequency.

This preliminary analysis shows that several hundred meters are necessary for frequencies around 5 MHz.

If it is not legally possible to impose constraints on systems located more than 3 kilometres from a fixed military reception station, the example shows that constraints may have to be imposed depending on the mutual operating conditions in areas several hundred meters from fixed military reception stations.

A6.2.5 Aggregation effects

It would be relevant to examine whether the accumulation of emissions related to WPT-EV can exceed certain critical thresholds for radio communications. This study does not seem to have been carried out elsewhere than in the article [56]. The assumptions made give significant disturbance distances depending on the frequency range and the density of chargers. Further studies will be necessary to compare the results.

Here, it is proposed the same approach as in the previous paragraphs, but considering an aggregation of chargers.

The addition of noise contributions from several WPT-EV chargers depends on the number of sources, their relative distance, and the nature of the electromagnetic radiation.

A6.2.5.1 Case of a small number of chargers

When several chargers operate nearby, their electromagnetic fields add up in power.

If it is assumed that their emissions are uncorrelated (i.e. with random phases), the addition follows the following statistical rule:

$P_{total} = N * P_{individual}$

With:

- P_{total} is the total received power;
- N is the number of WPT-EVs;
- $P_{individual}$ is the power transmitted by one WPT-EV.

In terms of noise level (in dB), this is equivalent to adding logarithmically:

$L_{total} = L_{individual} + 10*\log10(N)$

This means that each multiplication by 10 of the number of chargers would increase the total noise by 10 dB. This is a worst-case scenario.

A6.2.5.2 Effect of spatial dispersion

If the chargers are spread over a large area, the waves undergo attenuation with distance. In this case, the total power perceived at a given point is calculated by integrating the contributions of each source, taking into account:

- Attenuation of the fields with distance
- Superposition of waves (constructive or destructive)
- Signal propagation (ground wave, diffraction)
- This data need to be integrated into a larger simulation.

The study [56] deals with the case of aggregation of WPT-EV chargers. It considers an aggregation of 500 chargers on an island. According to the assumptions made there, the sum of the interferences can affect the background noise over several hundred kilometres.

A6.2.5.3 Consequences

If the chargers are numerous and concentrated, the increase in noise can be significant locally. Long-distance effects must be assessed.

If the chargers are dispersed, the addition of noise follows a progressive sum of contributions, which can impact radio systems to a lesser extent but over a larger area.

A cluster of chargers can be considered that would each comply with the ERC Recommendation 74-01 [5]. They are co-located.

By performing the calculations with the above assumptions, we can plot the hypothetical increase in the median noise level according to the number of chargers.

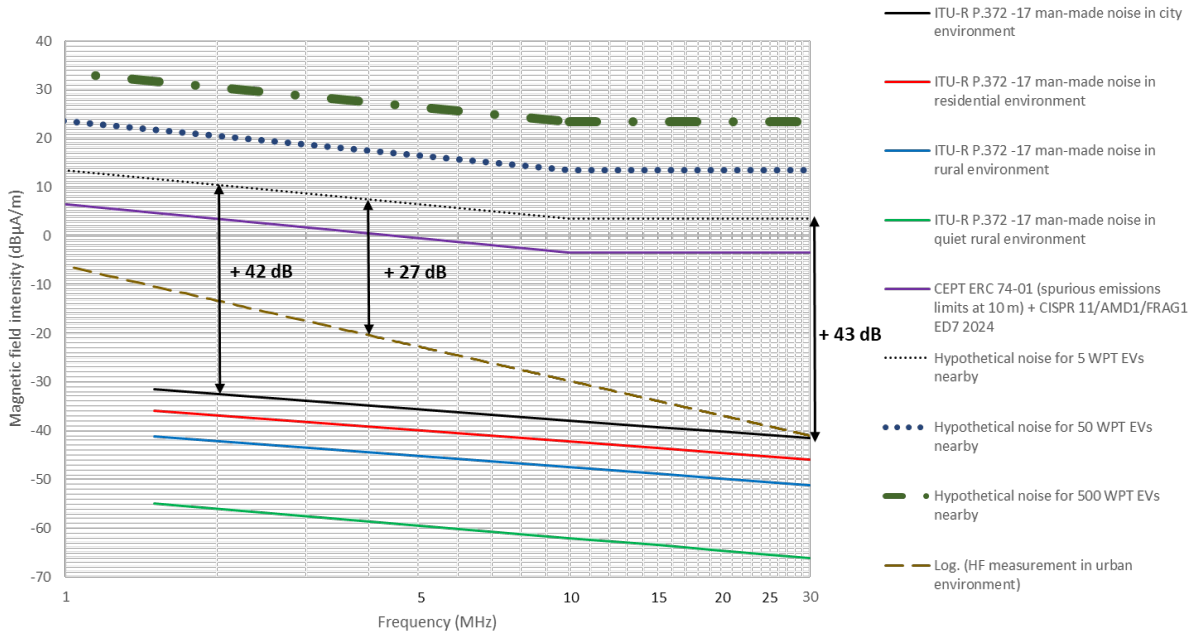


Figure 182: Hypothetical noise increase (worst case) for an aggregation of WPT-EVs

By considering the worst-case scenario, i.e. that all chargers would operate simultaneously, it is observed that a simple cluster of 5 chargers can cause an increase in overall noise of +20 dB to +43 dB depending on the frequency, at 10 meters. Referring to the median ITU urban noise level, we are about 40 dB above.

We insist on the fact that this is the worst-case scenario: there is little chance that a cluster of chargers will increase noise across the entire HF band. These will rather be harmonics on a few frequencies, whose maximum levels can reach the calculated thresholds. This is to raise awareness of the potential impact of harmonics on one or more frequencies.

This would make it impossible to receive HF signals for most signals that do not have a sufficient signal-to-noise ratio. As a reminder, the "HF measurement in urban environment" interpolation is an average of a real signal measurement in an urban environment. On the real measurement, it was found that less than 20% of the received signals were above the "ERC Recommendation 74-01" level.

A6.2.5.4 Conclusion of unwanted emission perturbation from an aggregation of WPT-EVs on the mobile and fixed service receiver in HF military frequency band

Further studies and measurements need to be carried out, by aggregating properly shielded chargers (from the power supply to the coil), developed beyond the prototype stage.

Indeed, in the ECC Report 289, p.25, can read in section 3.3 it can be read that Radiated emission measurements of real WPT-EV systems (“System 1 – 11 Kw”): “Any higher frequency emissions – for example, especially the emissions above 10 MHz, which exceed the proposed […] limit line […] are not representative for a final WPT-EV system. Those emissions occur primarily due to the prototype character of the WPT system, which consisted of special components such as unshielded laboratory supplies, prototype housings, etc.”.

If harmonics are already observed outside the current standard limits, the aggregated effect is likely to be worsened in the HF band.

The aggregation effect exists. Multiple WPT-EV systems have a higher potential of interference than one WPT-EV system. Several factors like different phase, different frequency of operation, actual emissions instead maximum allowed emissions and non-ideal environments (additional shielding) have not been taken into account in this study.

A6.2.6 Reduction of the magnetic field

An interesting study [57] deals with techniques to reduce the magnetic field generated by WPT-EV.

In this study [57], a 100-kW-class WPT system was built with the aim of reducing the radiated magnetic field strength. Three techniques are tested:

- Opposite-phase transfer: reduction of at least 16 dB;
- Frequency hopping spread to reduce the fundamental (although this makes harmonics harder to characterize in the HF band): reduction of about 12 dB;
- Low-pass filters to decrease the harmonic frequencies.

A 10 meters’ anechoic chamber was used to measure the radiated magnetic field strength of this WPT system.

The results confirmed the compatibility of the three proposed techniques, with a global perturbation reduction of 30 dB. This study technically demonstrates that reductions in harmonic emissions are possible.

Combining these techniques with the protection of other charger components, such as shielding their power supply to avoid high-frequency harmonics, opens up interesting possibilities for reducing the impact of future WPT-EV charger installations on military telecommunications. The upcoming arrival of dynamic chargers, used with even higher powers, will also need to be studied.

A6.2.7 New studies and measurements proposals

- Reception with an electrical (E-Field) antenna (example: 10-meter whip) for a distance of 10 meters;

- Reception with a magnetic (H-Field) antenna (example: Rohde & Schwarz HFH2-Z2 magnetic loop) for a distance of 10 meters;
- Land military vehicle equipped with an HF antenna, parked or driving in a street where one or more chargers are located.

A6.3 SENSITIVITY EXTRAPOLATION CALCULATION

A6.3.1 Proposed approach

-121 dBm/3 kHz = -115.77 dBm/10 kHz (through $10\log\left(\frac{10kHz}{3kHz}\right) = 5.23\ dB$)

Conversion to Watts: Pw = $2{,}64*10^{-15}$ W

Effective antenna surface at a frequency "f" (Hz): Aeff = $\lambda^2/4\pi$ with $\lambda=c/f$ (with c=3*108m/s) – considering an isotropic antenna

Power density S (W/m²): Pw/Aeff

Electric field E = $\sqrt{S * 120\pi}$ (V/m)

Conversion: electric field E to magnetic field H (through far-field approximation): H = $\frac{E}{377}$ (or HdB = EdB – 51.5)

A6.3.2 Reminder of current recommendations

General documents dealing with radio electric noise in the HF range express it in terms of electric field with the unit decibel relative to a microvolt per meter (dBµV/m) while documents dealing with radio electric noise generated by WPT-EVs express it in terms of magnetic field in another unit only which is the decibel relative to a microampere per meter (dBµA/m).

The reality is that these noises are not directly comparable. Only the components of distant (in the far-field) radiation sources can have electric and magnetic field components in a known proportion, given by the formula E/H = 120π Ω.

In many electromagnetic fields and techniques, the conversion between electric and magnetic field is implicitly performed by this formula, often inadequate but allowing easier calculations.

Most of the studies mentioned in the this addendum to ECC Report 289 consider magnetic-filed measurements made at 10 meters from a WPT-EV charger. The comparison between the levels of disturbance produced by WPT-EV expressed in magnetic field and the levels of radio electric noise observed and expressed in electric field, is not correctly performed by the conversion mentioned above. Indeed, the noises to which users of radio electric waves are confronted for the reception of functional and useful signals are, predominantly, of an electrical nature.

Military and professional reception installations then have the choice of capturing the magnetic components of the signals offering a sensitivity gain often better, by a factor of one hundred (20 dB) to one thousand (30 dB). An electric antenna will be more sensitive to an electric field and less sensitive to a magnetic field and the reverse is true for a magnetic antenna.

A6.3.2.1 Limits in ERC Recommendation 70-03 (Short Range Devices) Table 1, for non-specific Short Range Devices (extracted from ETSI EN 300 330)

Table 34: H Field limits at 10 m

The frequency ranges and limits of the present document are shown in table 2. The limits are based on the European Commission Decision for SRDs [i.10], CEPT/ERC/REC 70-03 [i.1].

Table 2: H-field limits at 10 m

Frequency range (MHz)	H-field strength limit (H_f) dBμA/m at 10 m or specified in mW e.r.p.
0,009 ≤ f < 0,090	72 descending 3 dB/oct above 0,03 MHz or according to note 1 (see note 5)
0,09 ≤ f < 0,119	42
0,119 ≤ f < 0,135	66 descending 3 dB/oct above 0,119 MHz or according to note 1 (see notes 3 and 5)
0,135 ≤ f < 0,140	42
0,140 ≤ f < 0,1485	37,7
0,1485 ≤ f < 30	-5 (see note 4)
0,315 ≤ f < 0,600	-5
3,155≤ f < 3,400	13,5
4,234	9 (see note 9)
4,516	7
7,400 ≤ f < 8,800	9
10,2 ≤ f < 11,00	9
12,5 ≤ f ≤ 20	-7
6,765 ≤ f ≤ 6,795	42 (see notes 3 and 7)
26,957 ≤ f ≤ 27,283	42 (see note 3)
13,410 ≤ f ≤13,553, 13,567 ≤ f ≤ 13,710	9 (see note 6)
13,110 ≤ f ≤ 13,410, 13,710 ≤ f ≤ 14,010	-3,5 (see note 6)
12,660 ≤ f ≤ 13,110, 14,010 ≤ f ≤ 14,460	-10 (see note 6)
11,810 ≤ f ≤ 12,660, 14,460 ≤ f ≤ 15,310	-16 (see note 6)
13,460 ≤ f ≤ 13,553, 13,567 ≤ f ≤ 13,660	27 (see note 6)
13,360 ≤ f ≤ 13,460, 13,660 ≤ f ≤ 13,760	Linear transition from 27 to -3,5 (see note 6)
13,110 ≤ f ≤ 13,360, 13,760 ≤ f ≤ 14,010	-3,5 (see note 6)
12,660 ≤ f ≤ 13,110, 14,010 ≤ f ≤ 14,460	-5 (see note 6)
13,553 ≤ f ≤ 13,567	42 (see note 3) or 60 (see notes 2 and 3)
27,095	42

Table 35: Limits in ERC Recommendation 74-01

2.1.3	Short range inductive devices operating below 30 MHz (in transmit mode) (Note 3)	9 kHz ≤ *f* ≤ 10 MHz	27 dBμA/m (at 9 kHz then decreasing by 10 dB/decade) (Note 4)
		10 MHz < *f* ≤ 30 MHz	-3.5 dBμA/m (Note 4)
		f within the bands: 87.5-118 MHz, 174-230 MHz, 470-–694 MHz	-54 dBm
		30 MHz < *f* ≤ 1 GHz (except 87.5–118 MHz, 174–230 MHz, 470–694 MHz)	-36 dBm
		1GHz < *f* ≤ FUPPER (see *recommend 3*)	-30 dBm

Table 36: Limits in CISPR/B/648/DC (2015-12-11) – Class B

Table 12 – Electromagnetic radiation disturbance limits for class B group 2 equipment measured on a test site

Frequency range MHz	Limits for a measuring distance D in m					
	Electric field				Magnetic field	
	D = 10 m		D = 3 m b		D = 10 m	D = 3 m
	Quasi-peak dB(µV/m)	Average a dB(µV/m)	Quasi-peak dB(µV/m)	Average a dB(µV/m)	Quasi-peak dB(µA/m)	Quasi-peak dB(µA/m)
0,15 – 4	–	–	–	–	14,5 decreasing linearly with the logarithm of frequency to -7,7	39 decreasing linearly with the logarithm of frequency to 3
4 - 11					-7,7 increasing linearly with the logarithm of frequency to -0,2	
11 - 30					-0,2 decreasing linearly with the logarithm of frequency to -7	

A6.3.2.2 Limits in CISPR11 AMD1 FRAG1 ED7 (2024) [59]

"The baseline of the proposed limits was also brought from the ERC Recommendation 74−01 for Short Range inductive Devices operating below 30 MHz in transmit mode [5].

Unwanted emission level in the spurious domain applied to the limit values of unwanted emissions other than the fundamental frequency band. The proposed limits level of the baseline for Class B equipment are as follows: 27 dBµA/m, for (at 9 kHz then decaying by 10 dB/decade) 9 kHz ≤ f ≤ 10 MHz, at 10 m measurement distance. For class A equipment, 15 dB higher level as class B was proposed."

The below figure summaries the current recommendations.

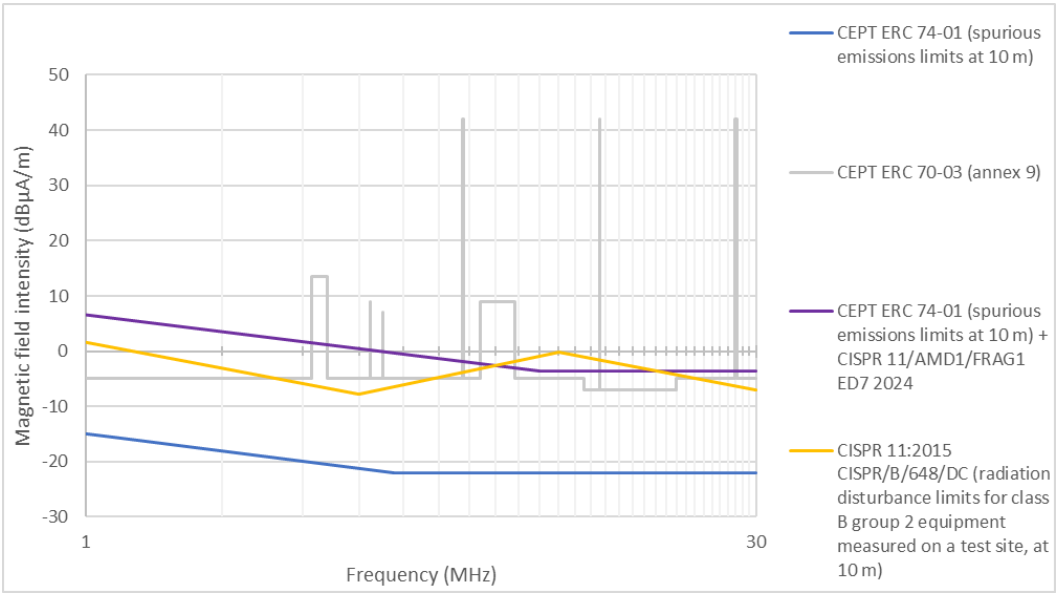


Figure 183: WPT-EV current recommendations

As a reminder, differences between Class A and Class B: "If a piece of equipment is categorised as CISPR 11 Class A, it is suitable for use in industrial environments and hospitals. If a piece of equipment is used in a residential setting (for which CISPR 11 Class B standard is required), this equipment may not offer adequate protection against radio frequency communications. The user may need to take measures to limit these radio frequencies, such as moving or reorienting the device." WPT-EVs are considered Class B equipment.

A6.3.2.3 MIL-STD-461G

This standard is cited for informational purposes. The MIL-STD-461G standard [82] is a reference for electromagnetic compatibility (EMC) for military equipment. It imposes limits on electromagnetic emissions and susceptibility to interference.

Here are some of the interesting requirements to study in light of WPT-EVs.

Table 37: Extract of requirements from MIL-STD-461 G

Requirement	Applicability	Potential application to WPT-EV
CE101	Conducted emissions, mains power (30 Hz – 10 kHz)	Mainly concerns low frequencies, but may affect harmonics of WPT-EVs if they generate signals below 10 kHz.
CE102	Conducted emissions, power supply (10 kHz – 10 MHz)	Direct impact on HF from 1.5 to 10 MHz. Would imply that WPT-EVs must limit their conducted emissions on the power grid, as these disturbances can propagate and then radiate via other equipment.
RE101	Radiated emissions, magnetic field (30 Hz - 100 kHz)	Would imply that WPT-EVs must respect a minimum emission threshold for the magnetic field.
RE102	Radiated emissions, electric field (10 kHz – 18 GHz)	Applies limits on radiated emission in electric field. Directly concerns the VLF-LF and HF bands, which means that WPT-EVs must respect a maximum emission threshold so as not to disrupt military communications.
RE103	Radiated emissions, spurious and harmonics (10 kHz to 40 GHz)	Harmonic limits for WPT-EVs.
CS101	Conducted susceptibility, power supply (30 Hz – 150 kHz)	Checks that equipment can operate without being disturbed by interference in this frequency range. Potential impact if a WPT-EV generates harmonic disturbances in HF via its power supply.
CS114	Susceptibility to induced RF currents (10 kHz – 200 MHz)	Test the ability of equipment to function despite induced HF currents. If a WPT-EV generates a magnetic field that is too strong in VLF-LF or HF, it could affect sensitive military equipment.
RS103	Radiated Susceptibility, Electric Field (2 MHz – 18 GHz)	Verify that military equipment does not experience interference from an external electromagnetic field. If a WPT-EV emits too strongly in 2-30 MHz, it could interfere with military HF communication systems.

The values to be respected are mostly presented in the form of frequency templates. For readability purposes, they are not recalled here.

However, there are some limits. For example, the requirement RE103 is not applicable to +/-5% of the fundamental frequency of the transmitting system or its bandwidth, considering the larger of the two.

If these requirements are deemed relevant, it will be necessary to examine the application conditions in detail in order to compare them with any future civil standards that will be issued regarding WPT-EV chargers.

ANNEX 7: UPDATED ANALYSIS ON THE IMPACT OF WPT-EV ON CIVIL AVIATION SYSTEMS (HF COMMUNICATION SYSTEM AND NON DIRECTIONAL BEACON)

A7.1 INTRODUCTION

ECC Report 289 provides the preliminary results of the studies on the impact of WPT-EV in 79-90 kHz on radiocommunication services operating below 30 MHz. The civil aviation community has two systems operating below 30 MHz:

- Non directional beacon (NDB) operating under the aeronautical radionavigation service (ARNS)
- HF communications operating under the aeronautical mobile (route) service (AM(R)S)

This study presents these systems, and provides their technical. This study only provides preliminary results for single entry interference cases. It could be completed by aggregate studies.

This study assumed:

- WPT-EV systems contain interfering emissions in the direction of the victim receiver at the level of the limits imposed in IEC 61980-1 [7], which are limits measured at a 10 m distance derived from limits from CISPR 11 edition 7.
- that the emissions are perfectly polarised the same way as the victim receiving antenna.

For more practical considerations, the characteristics of specific WPT-EV systems and their physical setup in relation to a victim receiver could be considered on a case by case basis.

A7.2 CIVIL AVIATION SYSTEMS OPERATING BELOW 30 MHZ

A7.2.1 Non directional beacons

A7.2.1.1 Operational description

NDBs support short- and medium-range navigation. With appropriate automatic direction finder (ADF) equipment on board an aircraft, the pilot can determine the bearing of the station or can “home” on the station. NDBs are mainly used as a non-precision instrument approach aid, either in conjunction with an ILS (then designated as a “locator”), or to define air routes/airways. NDBs are extensively deployed at aerodromes for general aviation. Although NDBs are comparatively inexpensive navigation aids and relatively simple to install and maintain, bearing information derived from NDBs is not very precise and lightning, precipitation static, etc., cause intermittent or unreliable signals resulting in erroneous bearing information and/or large oscillations of the radio compass needle. Frequencies used for NDB are prone to night effects, whereby, due to ionosphere propagation (reflection), significant errors due to the reception of signals from distant NDBs may occur. This night effect increases with assigned frequency of operation.

Aeronautical NDBs at coastal locations are also used by the maritime service, and in the reverse sense, beacons provided for maritime purposes are potentially usable by aviation.

ICAO Doc 9718 (Spectrum handbook) [84] indicates that “for international purposes, the future air navigation systems (FANS) scenario foresaw a reduction in the role of NDBs in the future due to, inter alia, the emergence of GNSS as the future system for a range of navigation services, including those for oceanic and low-density continental airspace.” However, the ICAO policy consists in safeguarding the current allocations to the aeronautical radionavigation service until NDBs have been phased out.

A7.2.1.2 Technical description

The non directional beacon is an MF transmitter which radiates an uninterrupted carrier in the range 190 kHz to 535 kHz. The carrier is amplitude modulated by a tone of either 400 Hz or 1020 Hz which is used to key a two or three letter morse identifier. The ident is transmitted at a rate of between 1 and 7 times per minute

depending upon the procedure which the beacon is supporting. After tuning to a particular NDB, the pilot uses the audible ident as a confirmation that the correct beacon has been selected.

The frequency management of NDBs is specified in ICAO Annex 10 Volume V [83], section 3.2 and in ITU-R Radio Regulations Appendix 12 [14].

A7.2.1.3 Protection criteria

This document investigates the separation distance between WPT-EV transmitters and NDB/ADF receivers in order to fulfil the following 2 different protection criteria:

NDB/ADF interference threshold computed from I/N = -6 dB, on top of which a 6 dB safety margin is added.

Interference threshold extracted from ECC Rep 067 (electrical field) which corresponds to a 3 dB degradation level. A 6 dB safety margin is added, consistently with the approach of ECC Report 333 [46].

A7.2.2 Aeronautical HF communication

A7.2.2.1 Operational description

The global aviation HF frequency bands between 2850 kHz and 22000 kHz provide aviation with a means for long-distance (beyond the radio horizon) communications. HF communications consist of both air-ground voice and HF data link (HFDL) communications. Both voice and HFDL enable aircraft to still communicate when moving outside of VHF coverage (e.g. oceanic, polar or remote areas) or during loss of satellite communications. Effective HF communication can be maintained up to thousands of kilometres between a ground station and the aircraft.

The extended range of HF operations is achieved through sky wave propagation, which uses the ionosphere and the Earth's surface to effectively "bounce" the signal beyond normal radio line of sight. As the ionosphere varies depending on the time of day and solar activity, a single HF ground station may cycle through multiple aeronautical frequencies from 2 MHz up to 22 MHz throughout the day to ensure communications.

HF is still required as a means for long-range communications for all aircraft operating in oceanic or remote regions and is an integral part of the associated safety case. HFDL has continued to evolve to support more aeronautical operational control (AOC) and ATS applications, such as controller-pilot data link communication (CPDLC) and ADS-C reporting and as of 2017 over 3000 aircraft are equipped with HFDL. Consequently, the HF channel capacity required for contingency planning continues to grow, though future requirements are expected to be met in the currently available frequency bands.

A7.2.2.2 Technical description

HF voice is used for both ATS and AOC communications worldwide. Using an upper single sideband (suppressed carrier) amplitude modulation (USB) for 3 kHz channels, HF ground stations transmit up to 6 kW of power. Use of the selective calling (SELCAL) notification system by ground stations reinserts the carrier for the duration of the SELCAL message to ensure reception by the aircraft.

HFDL also uses 3 kHz USB upper sideband channels, using a half-duplex digital transmission to communicate between the HF ground station and the aircraft on the same frequency. Its adaptive modulation rate provides resilience to interference, while also regularly scanning the other HF frequencies to select the most efficient channel as the ionosphere conditions change.

A7.2.2.3 Protection criteria

This document investigates the separation distances between WPT-EV transmitters and NDB/ADF receivers considering a HF interference threshold computed from I/N = -6 dB, on top of which a 6 dB safety margin is added.

A7.3 METHODOLOGY AND ASSUMPTIONS FOR COMPATIBILITY STUDIES BETWEEN WPT-EV AND CIVIL AVIATION SYSTEMS

The methodology for compatibility studies between WPT-EV and civil aviation systems is consistent with the methodology introduced in A5.3.

A7.3.1 WPT-EV radiated field

This analysis considers the WPT-EV magnetic strength limit specified by the standard IEC 61980 [7] for class A (equipment suitable for use in all locations other than those allocated in residential environment and those directly connected to a low voltage power supply network which supplies buildings used for domestic purposes) and class B equipment (equipment suitable for use in locations in residential environment and in establishments directly connected to a low voltage power supply network which supplies buildings used for domestic purposes).

Figure 184 illustrates the WPT-EV electric and magnetic fields limits for class A and class B equipment, measured at 10 m in a 10 kHz reference bandwidth. The electric field limit is derived with the following formula, which applies in the far field:

$$H_{spur} = \frac{E_{spur}}{120\pi}$$

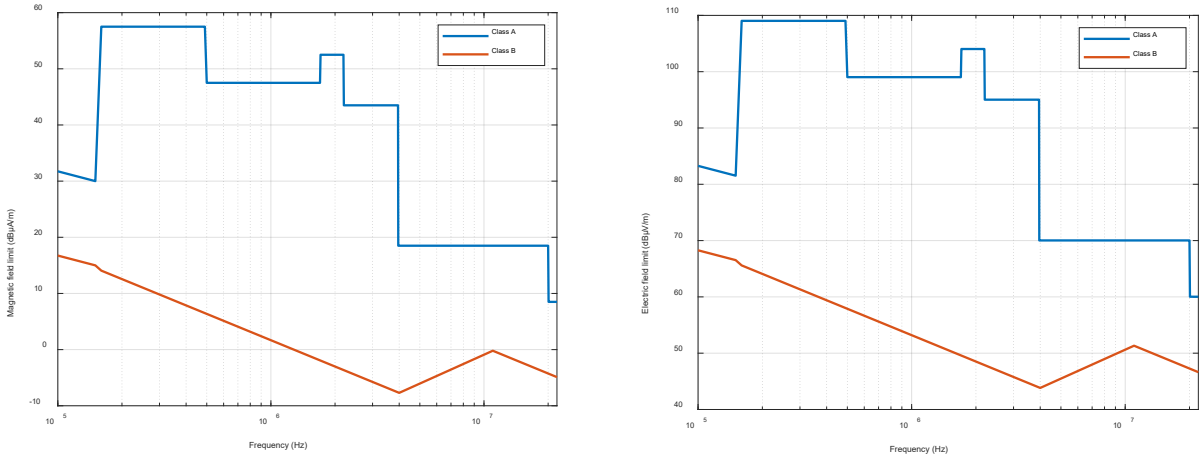


Figure 184: Magnetic and electric field limits, from IEC 61980-1 [7]

A7.3.2 Propagation attenuation

This study models the radiated field by WPT-EV similarly to the field generated by small circular loop. The components of the electric and magnetic field vary with the distance according to the following equations.

$$E_r = E_\theta = 0$$

$$E_\varphi = -\frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{jk}{r} + \frac{1}{r^2}\right)\sin(\theta)$$

$$H_r = \frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{2}{\eta r^2} + \frac{2}{j\omega\mu r^3}\right)\cos(\theta)$$

$$H_\theta = \frac{j\omega\mu M}{4\pi} e^{jkr}\left(\frac{j\omega\varepsilon}{r} + \frac{1}{\eta r^2} + \frac{1}{j\omega\mu r^3}\right)\sin(\theta)$$

$$H_{\varphi} = 0$$

$$k = \omega\sqrt{\mu\varepsilon}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

$$M = \pi I a^2$$

- M is the magnetic moment;
- μ is the permeability of free space;
- ε is the permittivity of free space;
- r is the distance between the WPT-EV transmitter and the receiver;
- $\omega = 2\pi f$, where f is the frequency of the receiver.

As an illustration, Figure 187 represents $E_{dB\mu V/m}$ and $H_{dB\mu A/m}$ as a function of r, where the magnetic moment M is chosen to meet the WPT-EV magnetic field limits $H_{spur} = -9.3\ dB\mu A/m$ at 10 m.

The plot was generated for a frequency $f = 238$ kHz, assuming $\theta = \pi/4$.

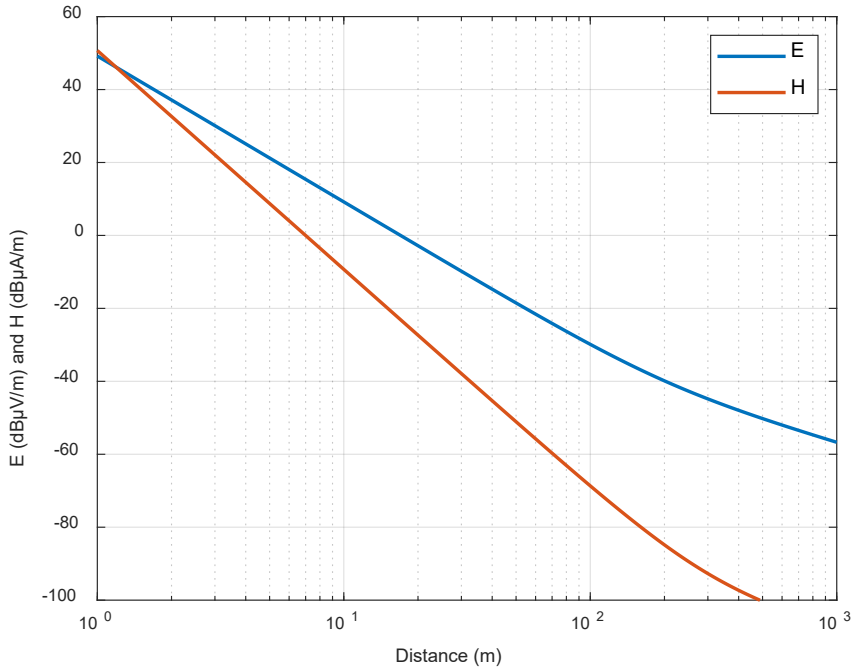


Figure 185: Evolution of electric and magnetic field as a function of distance

A7.3.3 Receiver antenna gain

This study assumes omnidirectional antenna with 0 dBi gain for NDB and HF airborne antennas.

Ground station for HF communication can be directive, with typical gain up to 13 dBi. However, noting that HF antennas would point above the horizon, it is not likely that WPT-EV impact the main lobe of the HF.

A7.3.4 Protection criteria values

A7.3.4.1 Interference threshold computed from I/N=-6 dB

In HF domain, the noise at the receiver antenna port is dominated by radio noise. In this study, the noise level is derived from Recommendation ITU-R P.37217 [25]. The derivation of the interference threshold is detailed in Table 38 for several frequencies, in quiet environment and in median city environment.

Table 38: Interference electric and magnetic field threshold (I/N = -6 dB)

	Quiet receiving site				Median city environment				
	190	535	2000	22000	190	535	2000	22000	Frequency (kHz)
External noise figure (dB)	73.3	61	45.3	22.7	93	81.8	67.5	40.4	Recommendation ITU-P.372-1, figure 2 [25] (Median city area)
Noise electric field strength (dBµV/m)	2.1	-1.2	-5.5	-7.3	21.8	19.6	16.7	10.5	Recommendation ITU-P.372, equation 8 [25] (in 10 kHz bandwidth)
Noise magnetic field strength (dBµA/m)	-49.5	-52.8	-57.0	-58.8	-29.7	-32	-34,8	-41.1	H = E/377
I/N protection ration (dB)	-6	-6	-6	-6	-6	-6	-6	-6	
Safety margin (dB)	6	6	6	6	6	6	6	6	According to ICAO policy (Doc 9718) [84]
Interference electric field threshold (dBµV/m)	-9.9	-13.2	-17.5	-19.3	9.8	7.5	4.7	-1.5	
Interference magnetic field threshold (dBµA/m)	-61.5	-64.8	-69.0	-70.8	-41.7	-44	-46.8	-53.1	

Figure 188 represents the electric and magnetic fields interference threshold computed from the I/N=-6 dB protection criteria.

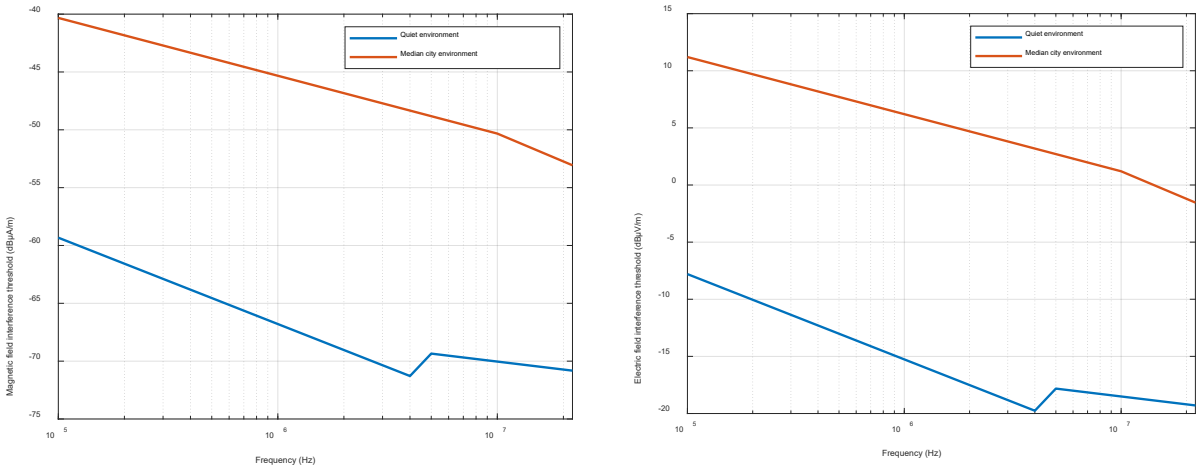


Figure 186: electric and magnetic fields interference threshold computed from the I/N=-6 dB protection criteria

A7.3.4.2 NDB interference threshold from ECC Report 333

ECC Report 333, annex 10 [46] assumes a permissible interference level of 21.9 dBµV/m. This value is computed from the required sensitivity for NDB receivers, which is 70 µV/m=36.9 dBµV/m. The protection criteria which is applied corresponds to a desired over undesired signal (D/U) power ratio of 15 dB. In addition, ECC Report 333, annex 10 adds a 6 dB safety margin in accordance with ICAO policy stated in ICAO Doc 9718 [84]. The resulting interference electric and magnetic fields thresholds are given in Table 39.

Table 39: Interference electric and magnetic field thresholds (from D/U=15 dB)

Max. tolerable interference electric field (dBµV/m)	21.9
Safety margin	6
Interference electric field threshold (dBµV/m)	15.9
Interference magnetic field threshold (dBµA/m)	-35.6

A7.4 RESULTS

The minimum separation distance between the WPT-EV transmitter and the aeronautical receiver is determined by finding the minimum distance r_{min} such that the WPT-EV electric and magnetic fields at r_{min} remains below the interference electric and magnetic field thresholds.

A7.4.1 Results for Class A WPT-EV

This section computes the minimum separation distance between WPT-EV equipment having an emission in the direction of a victim receiver, polarised in the same way as the victim receiver, and occurring at the limit indicated in IEC 61980-1 [7] for a Class A system.

Figure 187 represents the minimum separation distance between WPT-EV and aeronautical system as a function of the frequency. This minimum separation distance is determined by finding, for each frequency, the distance at which the magnetic and electric fields computed in section A7.3.2 are equal to the thresholds (see section A7.3.3).

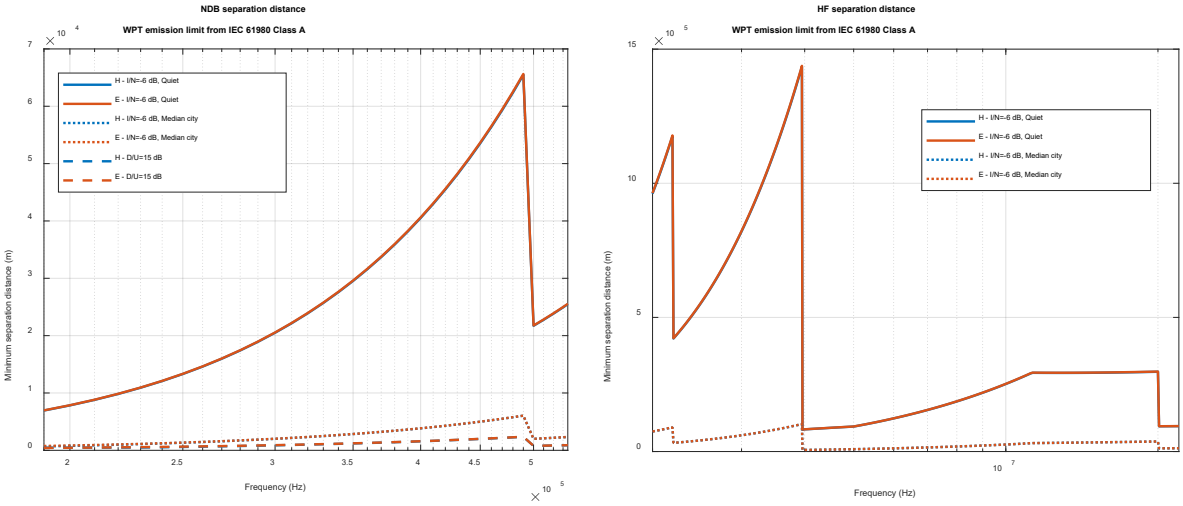


Figure 187: Minimum separation distance between WPT-EV and aeronautical systems, assuming WPT-EV electric and magnetic fields defined by IEC 61980 [7] for Class A equipment

Eventually, Table 40 summarises the different minimum separation distance for the different assumptions.

Table 40: Minimum separation distance assuming WPT-EV emission limits of IEC 61980-1 [7] Class A

		NDB		HF	
		Electric field	Magnetic field	Electrical field	Magnetic field
Thresholds computed from I/N=-6 dB	Median city area	6.05 km (at 490 kHz)	6.05 km (at 490 kHz)	103 km (at 3.95 MHz)	103 km (at 3.95 MHz)
	Quiet site	65.64 km (at 490 kHz)	65.48 km (at 490 kHz)	1438 km (at 3.95 MHz)	1435 km (at 3.95 MHz)
Thresholds computed from D/U=15 dB	Median city area	2.38 km (at 490 kHz)	2.36 km (at 490 kHz)	-	-7

A7.4.2 Results for Class B WPT-EV

This section computes the minimum separation distance between WPT-EV equipment having an emission in the direction of a victim receiver, polarised in the same way as the victim receiver, and occurring at the limit indicated in IEC 61980-1 [7] for a Class B system.

Figure 190 represents the minimum separation distance between WPT-EV and aeronautical system as a function of the frequency. This minimum separation distance is determined by finding, for each frequency, the distance at which the magnetic and electric fields computed in section A7.3.2 are equal to the thresholds (see section A7.3.3).

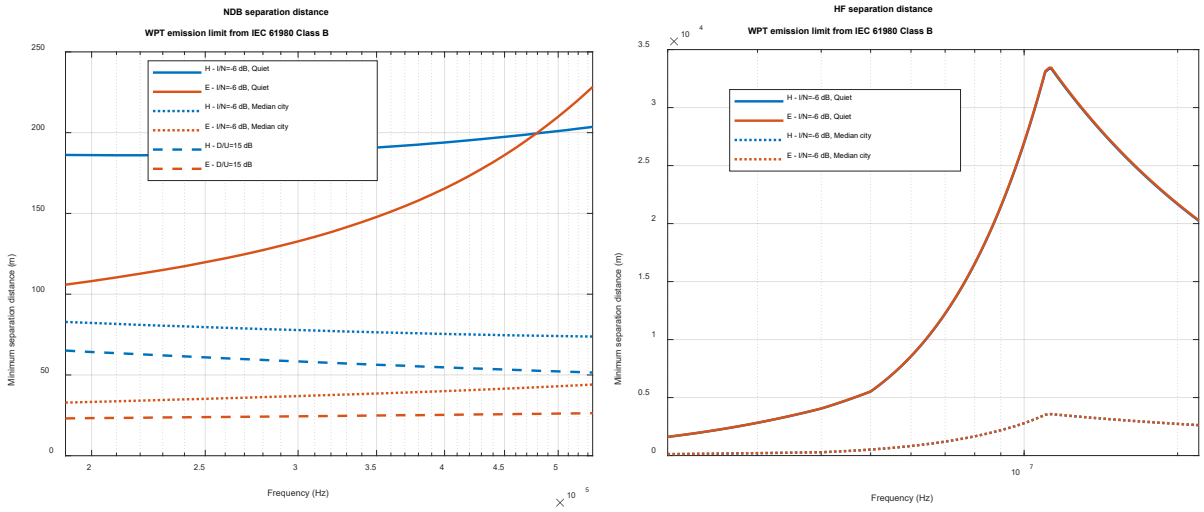


Figure 188: Minimum separation distance between WPT-EV and aeronautical systems, assuming WPT-EV electric and magnetic fields derived from IEC 61980-1 [7] Class B

Eventually, Table 41 summarises the different minimum separation distances for the different assumptions.

Table 41: Minimum separation distances assuming WPT-EV emission limits of IEC 61980-1 Class B

		NDB		HF	
		Electric field	**Magnetic field**	**Electrical field**	**Magnetic field**
Thresholds computed from I/N=-6 dB	Median city area	44 m (at 535 kHz)	83 m (at 190 kHz)	3.59 km (at 11.3 MHz)	3.58 km (at 11.3 MHz)
	Quiet site	228 m (at 535 kHz)	205 m (at 535 kHz)	33.46 km (at 11.3 MHz)	33.38 km (at 11.3 MHz)
Thresholds computed D/U=15 dB	-	27 m (at 535 kHz)	66 m (at 190 kHz)	-	-

A7.5 WPT-EV EMISSION LIMITS FOR PROTECTION OF HF COMMUNICATION SYSTEM AND NDB

This section computes the WPT-EV transmission limits in the frequency bands 190-535 kHz and 2-22 MHz that will allow the protection of NDB and HF communication systems.

A7.5.1 Minimum distance between WPT-EV and aviation systems

For non-precision approach such as NDB approach, the minimum altitude at which the pilot needs to see the runway before taking the decision to continue the landing, is 250 ft. This height may be increased on a case by case basis depending on the height of obstacles in the approach trajectory. Above that altitude, the pilot fully relies on the indication from NDB. As a consequence, it is expected that the separation distance between on-board NDB receiver and WPT-EV, at which NDB receiver must remain free from WPT-EV harmful interference, is 250 ft = 76 m.

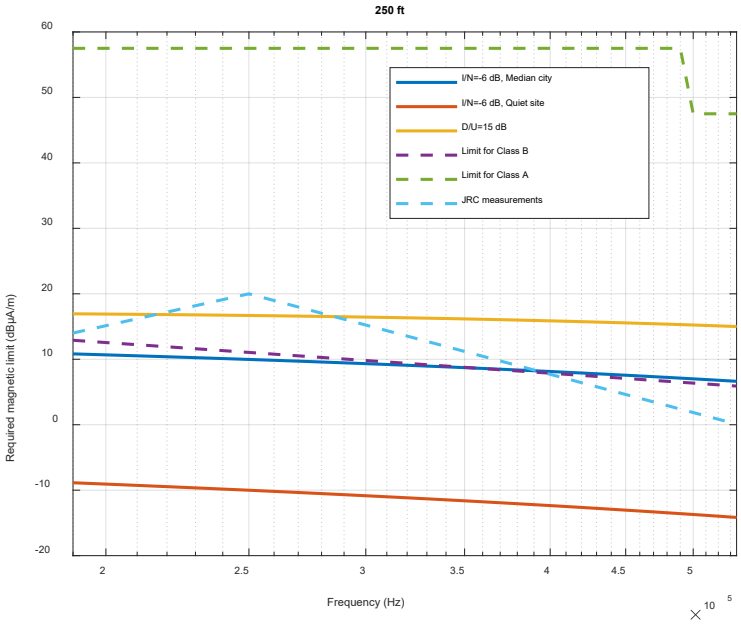


Figure 189: Required limit in the 190-535 kHz band for the protection of NDB

The concept of operation of HF communication is adapted on a case by case basis on the national civil aviation authorities. In this study, it is assumed that HF is required when the aircraft altitude is above 4500 ft. Below this altitude, it is assumed that the departure and arrival procedures rely on VHF communication. As a consequence, this study assumes that the minimum separation distance between on-board HF receiver and WPT-EV is 4500 ft = 1372 m.

However, it is expected that the separation distance between WPT-EV and HF ground stations can be lower. Analysing the different sites of HF ground stations in France, it seems that a separation distance of 400 m is a realistic assumption. Below this distance, it is expected that a coordination with civil aviation should take place, in order to decide on a case-by-case basis of the risk of interference on the ground receivers, depending on the environment surrounding the WPT-EV and the HF receiver.

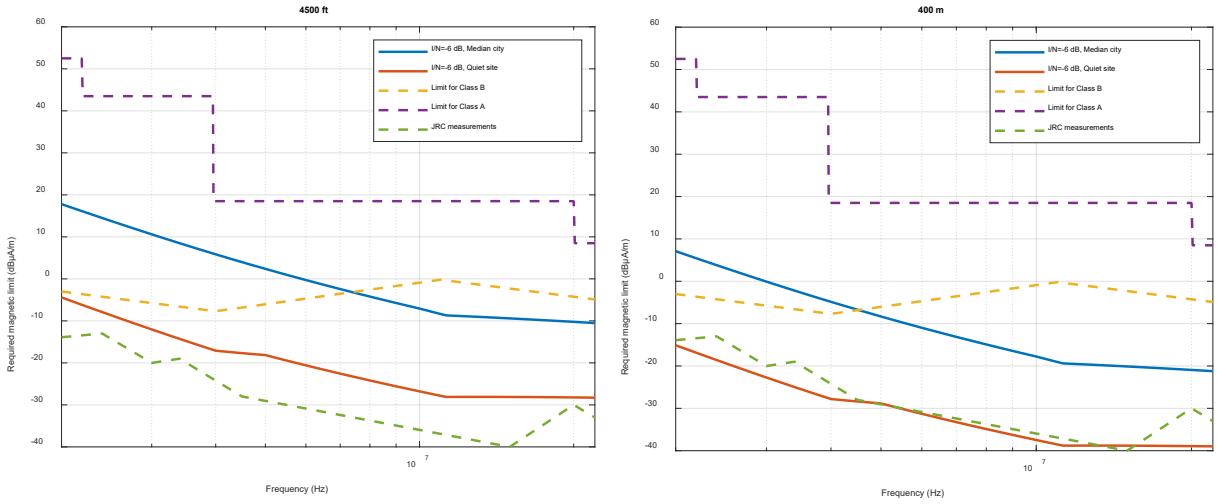


Figure 190: Required limit in the 2-22 MHz band for the protection of HF communication on-board (left) and ground (right) receivers

A7.6 SUMMARY

This study is a preliminary analysis of the impact of WPT-EV on two civil aviation systems, namely NDB and HF communications. This analysis contains several assumptions, in particular on the electric and magnetic field limits radiated by WPT-EV. Depending on the protection criteria selected to ensure NDB remains free from harmful interference as well as on the WPT-EV emission limits, the minimum separation distance between WPT-EV and NDB/ADF receivers ranges from 27 m to 228 m for Class B WPT-EV equipment and from 2.4 km to 65.7 km for Class A WPT-EV equipment. Likewise, minimum separation distance between WPT-EV and HF communication receivers is between 3.6 km and 33.5 km for Class B WPT-EV. Results show excessively high distances for WPT-EV Class A for HF communication protection. Eventually, this contribution proposes emission limits for WPT-EV in order to ensure the protection of civil aviation systems in their normal operations. Proposed limit to protect the ground receiver are computed assuming a separation distance of 400 m and proposes a coordination process if the WPT-EV should be deployed closer from the HF station.

This study only investigates single entry interference. It also does not investigate the impact of dynamic WPT-EV. Additional work is needed on the impact of aggregate WPT-EV and dynamic WPT-EV on civil aviation systems before to get a conclusion of the real impact of WPT-EV.

ANNEX 8: LOFAR STATIONS IN THE NETHERLANDS

Table 42: List of Core and Remote LOFAR stations in the Netherlands

Core Station Name	Latitude (N)	Longitude (E)	Remote station Name	Latitude (N)	Longitude (E)
CS001	52°54'41"	6°52'3"	RS106	52°52'27"	6°59'6"
CS002	52°54'54"	6°52'11"	RS205	52°51'27"	6°53'48"
CS003	52°54'57"	6°52'7"	RS208	52°40'10"	6°55'8"
CS004	52°54'52"	6°52'6"	RS210	52°19'51"	6°52'25"
CS005	52°54'51"	6°52'13"	RS305	52°53'58"	6°46'26"
CS006	52°54'53"	6°52'18"	RS306	52°53'25"	6°44'36"
CS007	52°54'56"	6°52'16"	RS307	52°48'12"	6°40'51"
CS011	52°54'50"	6°52'25"	RS310	52°45'52"	6°8'19"
CS013	52°55'5"	6°52'1"	RS406	53°1'4"	6°45'2"
CS017	52°54'57"	6°52'38"	RS407	53°5'33"	6°47'3"
CS021	52°55'4"	6°51'47"	RS409	52°58'50"	6°21'29"
CS024	52°54'29"	6°52'28"	RS503	52°56'42"	6°51'3"
CS026	52°54'58"	6°52'58"	RS508	53°14'24"	6°57'11"
CS028	52°55'33"	6°52'30"	RS509	53°24'32"	6°47'7"
CS030	52°55'20"	6°51'41"			
CS031	52°55'4"	6°51'32"			
CS032	52°54'45"	6°51'36"			
CS101	52°55'21"	6°52'52"			
CS103	52°54'57"	6°53'49"			
CS201	52°54'45"	6°52'58"			
CS301	52°54'21"	6°52'4"			
CS302	52°54'6"	6°50'57"			
CS401	52°54'51"	6°51'21"			
CS501	52°55'35"	6°51'57"			

ANNEX 9: ANALYSIS OF THE IMPACT OF UNWANTED EMISSIONS OF WPT-EV ON TERRESTRIAL AND MARITIME VLF AND LF MILITARY SYSTEMS

A9.1 INTRODUCTION

For military communications, the 9–150 kHz band is used to provide long-range communications. For radiocommunication services, unintentional interference can lead to degraded performance, increasing error probability and/or decreasing communication range.

In this study, protection distances are calculated in order to define the range outside which no harmful interference will occur to the radio communication systems. This distance depends on:

- The maximum field levels generated by the WPT-EV chargers;
- The minimum field levels that an affected radio service expects;
- And the attenuation due to the field's propagation between the WPT-EV chargers and the radio service systems.

The maximum field levels generated by the WPT-EV chargers are modelled in accordance with values in the European standard IEC 61980-1 [7].

The attenuation calculation due to the field propagation use the model of ERC REPORT 69 [9] and Recommendation ITU-R SM.2028-0 [10]. They provide procedure to calculate the protection distance between inductive systems and radio communication services using frequencies below 30 MHz.

A9.2 STUDY HYPOTHESIS AND PROCEDURE

A9.2.1 limits of radiated electromagnetic disturbances for WPT-EV chargers

The limits of radiated electromagnetic disturbances considered in this study, which includes the WPT system in the frequency range between 9 kHz and 150 kHz, can be found in the European standard IEC 61980-1 [7] for Class A and Class B WPT systems.

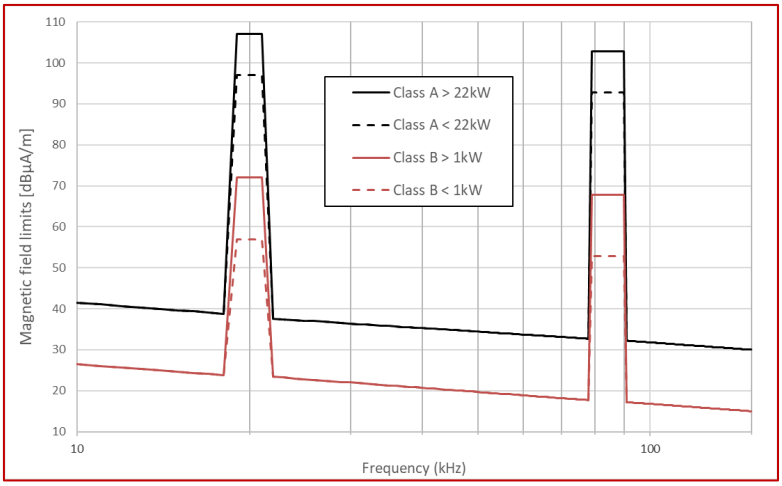


Figure 191: Limits of radiated magnetic field disturbances for Class A and Class B WPT systems

These values presented in dBµA/m are defined at a distance of 10m to the emission source (see Figure 191).

Class A equipment is equipment intended for use in all locations outside residential environments, and other than those directly connected to a low-voltage power supply network that supplies buildings for domestic use.

Class B equipment is equipment intended for use in locations in residual environments and in establishments directly connected to a low-voltage power supply network that supplies buildings for domestic use.

A9.2.2 Generic characteristics to protect NATO radio communication services

NATO radio communication services are divided into terrestrial and maritime services, each with their own protection criteria.

The two services can use both magnetic and/or electric antennas.

In this study, the following values are considered for a bandwidth of 200 Hz to avoid interfering with terrestrial services:

- For the VLF band (between 10 and 30 kHz): -25 dBµA/m (H) and 26.5 dBµV/m (E)
- For the LF band (between 30 and 100 kHz): -30 dBµA/m (H) and 21.5 dBµV/m (E)

Due to the confidential nature of the victim service, characteristics and a derivation of these values could not be provided. These values are derived from generic military protection criteria and modelling assumptions and should be interpreted within the context of the applied reference bandwidth and scenario assumptions.

Terrestrial fixed or mobile stations can be located in noise environments from "quiet rural" to "urban" as defined in Recommendation ITU-R P.372 [25].

To avoid interfering with maritime services, the value considered in this study is the atmospheric noise (value exceeded 99.5% of time) defined in Recommendation ITU-R P.372, for the electrical field. From the noise factor Fa (Figure 192), the electric field value is calculated and thereafter converted to magnetic field value using the free space impedance.

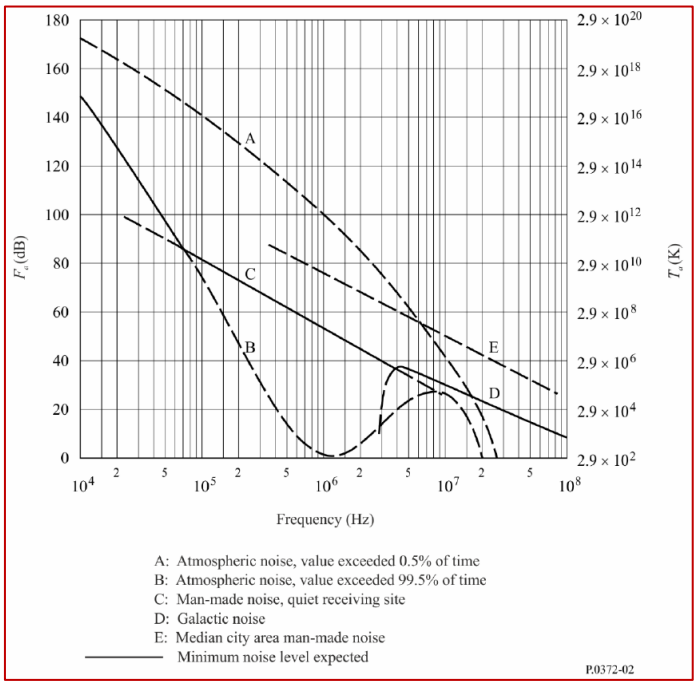
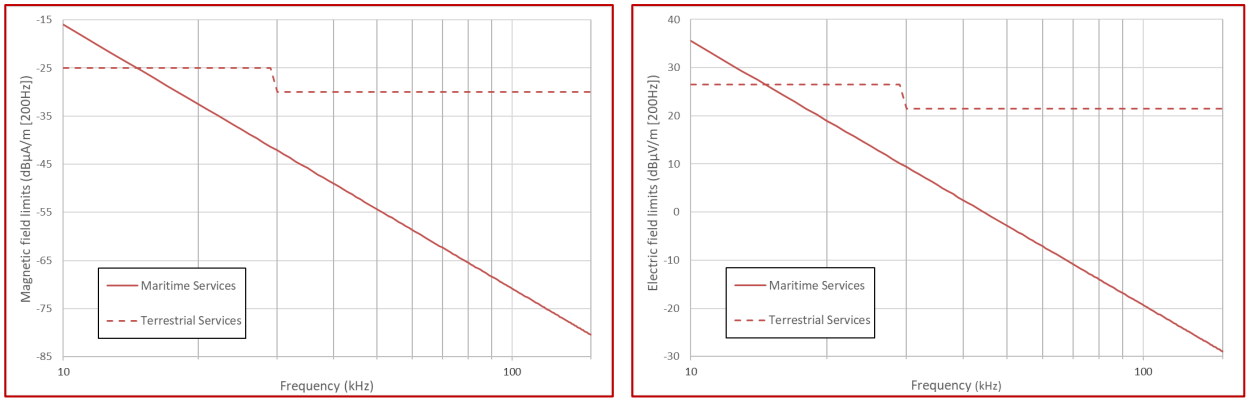


Figure 192: Recommendation ITU-R P.372 Noise factor Fa for 10 kHz and 100 MHz

Maritime mobile stations can be situated at remote places far from man-made noise sources. When ships are located in a harbour, the values are those defined previously for terrestrial services.

Figure 193 provides the values of magnetic (in dBµA/m) and electric (in dBµV/m) fields to avoid interference with a radio communication system calculated for the bandwidth of 200 Hz.



(a) **(b)**

Figure 193: Terrestrial and maritime services protection criteria for (a): Magnetic field, (b): Electric field

Most of these systems are designed for 24/7 operation. The operating bands allocated for each assigned frequency range from 100 Hz to 6 kHz.

A9.2.3 Protection distance calculation

Recommendation ITU-R SM.2028-0 [10] addresses the compatibility between inductive systems operating at frequencies below 30 MHz and radio communication services, providing a calculation procedure of protection distance between inductive and radio communication systems.

In this ITU-R Recommendation, based on the measurement of the magnetic field radiated by the inductive system and the calculation of the magnetic dipole moment, different attenuation models depending on the wavelength and the distance from the source are used to calculate the protection distance in the near field and far field conditions. The complete coverage range can be divided into four sub-ranges: inside the near field, close to the near field, at distance limited to the 20 dB/decade roll-off and distance extended into 40dB/decade roll-off.

For longer protection distances, the ground wave propagation is used as referred in Recommendation ITU-R P.368-10 [8]. In this study, two ground conditions are used in the following calculations: average ground ($\sigma = 10^{-3}$ S/m, $\epsilon_r = 22$) for separation distances with terrestrial services, and seawater conditions ($\sigma = 1$ S/m, $\epsilon_r = 80$) for separation distances with maritime services. The ionospheric propagation is not considered.

A9.3 RESULTS

The separation distances are calculated for the entire frequency band ranging from 10 kHz to 150 kHz. This study only focuses on the impact of out-of-band emissions.

A9.3.1 Minimum separation distance for WPT-EV class B

Figure 194 shows the separation distances for wireless charging systems with terrestrial military communication systems.

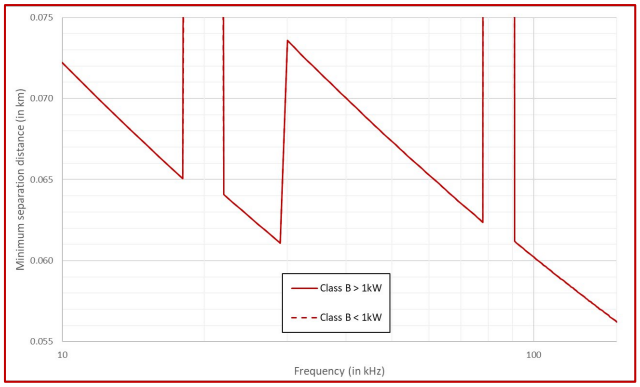


Figure 194: Calculated separation distances for Class B WPT-EV systems with terrestrial military communication services

The separation distances for out-of-band emissions decrease linearly with the logarithm of the frequency as is the case for the IEC61980-1 limits [7]. The change in generic constraints between the VLF and LF bands is visible at 30 kHz with an increasing step. The separation distances are between approximately 55 and 75 meters.

Figure 195 shows the separation distances with maritime military communication systems.

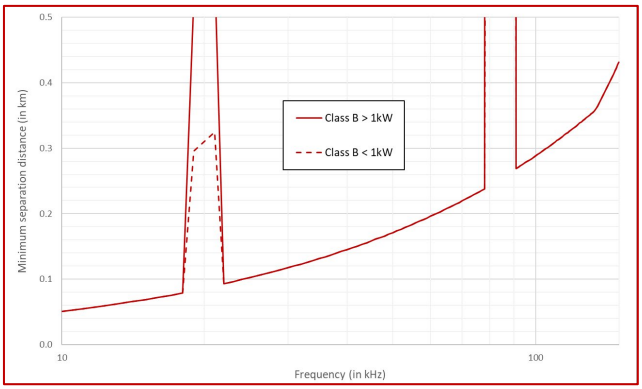


Figure 195: Calculated protection distances for Class B WPT systems with maritime military communication services at sea

The separation distances between WPT-EV with maritime communication systems operating at sea increase with the frequency due to the decrease of the atmospheric noise (Figure 197). The separation distances for out-of-band emissions vary from 50 meters at 10 kHz to around 400 meters at 150 kHz.

As per the use of the methodology given in Recommendation ITU-R SM.2028-0 [10], the separation distances in the near-field region (as it is the case here), are computed based on the H-field limits of the receiver and coaxial configurations. For receivers using antenna mostly susceptible to E-fields (which is maximum in coplanar configurations in this case of a small loop transmitting antenna), the distances would be lower.

A9.3.2 Summary of Minimum separation distance for WPT-EV class A and Class B

Calculations are reproduced for Class A > 22kW values. The below tables resume the protection distances calculated for WPT-EV systems for Class B (Table 43) and Class A (Table 44) with terrestrial and maritime military radio communication systems. As discussed in the section above, they are computed using magnetic field limits and assume coaxial configurations.

Table 43: Protection distances for Class B > 1kW WPT systems

Band	Services	Distances
10-150 kHz (unwanted domain)	Terrestrial or maritime in harbour	56 m – 74 m
	Maritime at sea	51 m – 432 m

Table 44: Protection distances for Class A > 22kW WPT systems

Band	Services	Distances
10-150 kHz (unwanted domain)	Terrestrial or maritime in harbour	100 m – 128 m
	Maritime at sea	91 m – 2.3 km

The protection distances of several hundred meters obtained for terrestrial communication receivers may be difficult to implement in practice.

A9.4 CONCLUSION

The impact of unwanted emissions from Wireless Power Transmission for Electric Vehicles (WPT-EV) on military radio communication services operating below 150 kHz is considered in this study. Separation distances are calculated for WPT-EV charger of Class A and Class B for unwanted emissions.

This single-entry study considers worst-case scenarios to illustrate the potential risks of interference from one WPT-EV charger with military communication systems (no frequency separation, over sea water propagation condition for maritime services, maximum radiated field levels at the limit of the current standards, magnetic receiving antenna). Separation distances are given for terrestrial systems and maritime systems operating in harbour as well as for maritime systems operating at sea (which operate under quieter levels of man-made noises). Computations use the model of Recommendation ITU-R SM.2028-0 [10], and since separation distances all lie in the near field region, they are based on magnetic field limits. Receivers using antennas more susceptible to electrical fields would thus be less susceptible, noting that both kind of antennas are used in practice by the systems under study. The protection distances calculated in this contribution provide orders of magnitude that suggest interference risks in practice.

The study indicates that WPT-EV deployment with unwanted emissions limits not stricter that those defined in IEC 61980-1 [7] may not sufficiently protect military terrestrial radiocommunication services. Furthermore, while worst-case assumptions have been considered, it is to be noted that this study did not consider the cumulative effect of interference from multiple WPT-EV.

The results of this study may need to be validated by field trials.

ANNEX 10: INTERFERENCE OF WPT-EV WITH RADIO STATIONS – REAL WORLD DATA FOR PROBABILITY ESTIMATION OF OCCURENCE OF WORST-CASE CONDITIONS

A10.1 SUMMARY

The data presented bin this sub-chapter shows that the probability of simultaneous occurrence of worst-case conditions (as assumed in the theoretical studies) is low, if real system properties of a series system according to IEC 61980 [7] are considered.

The WPT-EV system considered in this subchapter is designed to perform according to IEC 61980-1, table 8 (2020).

Table 45: IEC 61980-1, table 7 (2020), EMC limit for WPT-EV class A devices in 10 m distance

Frequency range in MHz	Magnetic field quasi-peak in dB(µA/m)
0.15 to 0.49	57.5
0.49 to 1.705	47.5
1.705 to 2.194	52.5
2.194 to 3.95	43.5
3.95 to 20	18.5
20 to 30	8.5

Table 46: IEC 61980-1, table 8 (2020), EMC limit for WPT EV class B devices in 10 m distance

Frequency range in MHz	Magnetic field quasi-peak in dB(µA/m)
0.15 to 4	14.5 decreasing linearly with the logarithm of frequency to -7.7
4 to 11	-7.7 increasing linearly with the logarithm of frequency to -0.2
11 to 30	-0.2 decreasing linearly with the logarithm of frequency to -7

Direct probability calculations via Monte Carlo Analysis require further details on the nature of the victim receiver link and research on some of the factors mentioned in this work.

A10.2 INTRODUCTION

Existing studies that aim on proposing separation distances or electric field limits are Minimum Coupling Loss methods that often neglect real world properties of WPT-EV. This annex intends to provide input that can be utilised for a Monte Carlo simulation on interference probability estimation.

The used measurements were conducted with series production charging systems and cars in 10 meter semi-anechoic chambers.

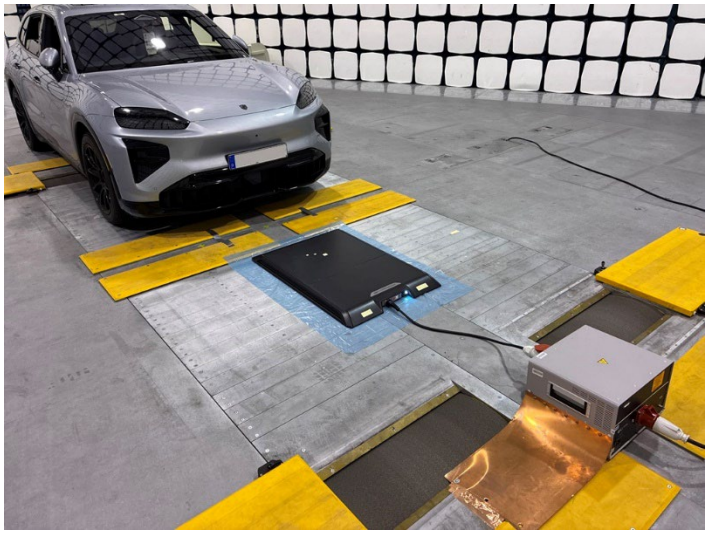


Figure 196: WPT-EV Ground Assembly with test vehicle

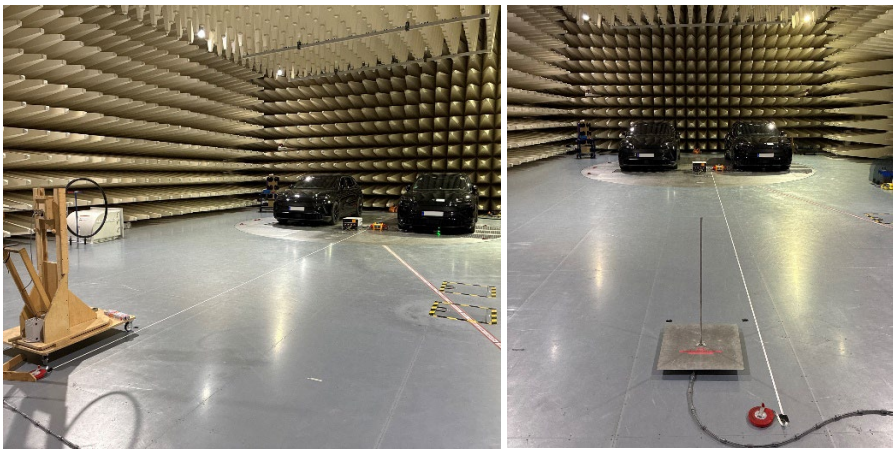


Figure 197: Antennas and setups used for measurements, H-Field (60 cm magnetic loop) and E-Field (1 m monopole)

A10.3 CATEGORISATION OF WPT EMISSIONS

Unwanted emissions of WPT-EV systems can be categorised in WPT-EV specific emissions and non WPT-EV specific emissions common to any kind of source of radio-frequency interference. Each of these two kinds of emissions may require different mitigation techniques.

WPT-EV specific:

- Actual resonant power transfer on fundamental frequency and its unwanted harmonics emitted via the main coil of the air-gap transformer;
- Power electronics noise emitted via main coil.

Non WPT-EV specific:

- Conducted emissions on LV AC mains cables and other interconnecting cables caused by conventional and switched-mode power supply (SMPS) components of the WPT-EV system, radiated by unshielded AC mains cables;
- Radiated emissions by power electronics and internal switched-mode power supplies, radiated through the housing and enclosure of the WPT-EV device;
- Emissions of radio devices and wireline communication components of WPT-EV systems that radiate via attached antennas and other data transfer or signalling lines.

This work concentrates on WPT-EV specific emissions.

A10.4 TIME COINCIDENCE

Static WPT-EV will predominantly be used to charge EVs on private ground in a daily fashion for commuting. It has little relevance for long distance traveling, as the charging time would be too long. The average daily commuting distance in Germany is about 18 km one way [86]. Assuming an energy consumption of 25 kWh/100km [87] and 90% efficiency of the charging system, this calculates to just below 1 hour of daily charging time or a duty cycle of 4.2%.

A study performed by National Centre for Charging Infrastructure, Germany in October 2024 [85] gives time probabilities for private charging, separated for users with and without PV-installation. More than 50% of the surveyed participants did own a PV-installation at the time of the survey.

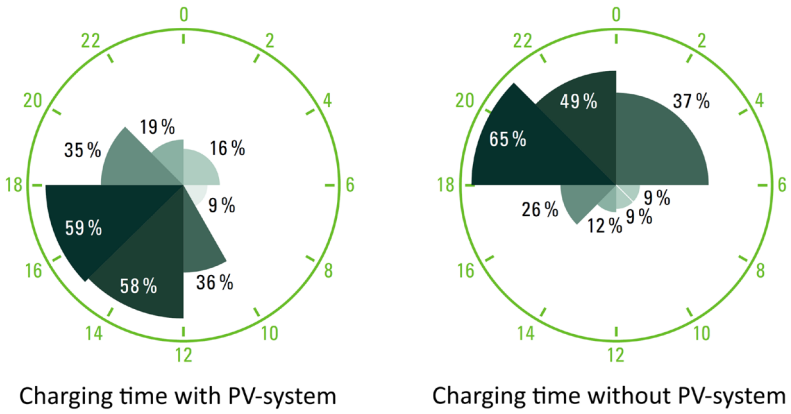


Figure 198: Average time of the day for EV charging with PV-installation (left) and without PV-installation (right) [85]

A10.5 LOCATION COINCIDENCE

The most WPT-EV charging stations can be expected either in a residential environment for private users or in a city or industrial environment for commercial users.

The below figure shows for a real world example the distribution of EV chargers and amateur radio stations as of March 2026. Additional EV chargers might be added in the future and some might be replaced by WPT-EV. As WPT-EV is considerably more expensive than conventional chargers, it will most probably not replace all of them.

In this example, the closest distance between a charging station and a victim receiver is about 50 m, including a residential building in between.

An article in tagesschau.de from 6 May 2023 [88] assumes about 1 mio private and commercially used EV charging stations in Germany. The dena Gebäudereport from December 2024 [89] gives a total number of ca. 28 mio one to six party houses, which is the predominant building style in this example area. These numbers hint that the exemplary distribution shown below is at least not unrealistic for an average residential area.

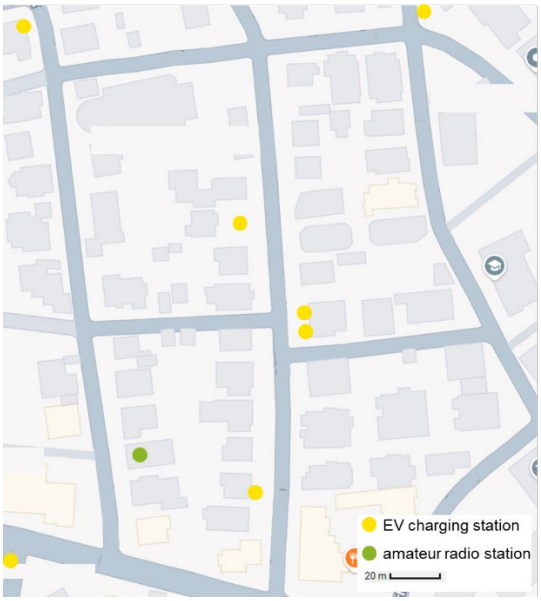


Figure 199: Real world example residential area with EV charging stations and an amateur radio station

With distance the emissions will attenuate accordingly. The below figure shows the signal attenuation when increasing distance from 10 to 30 m.

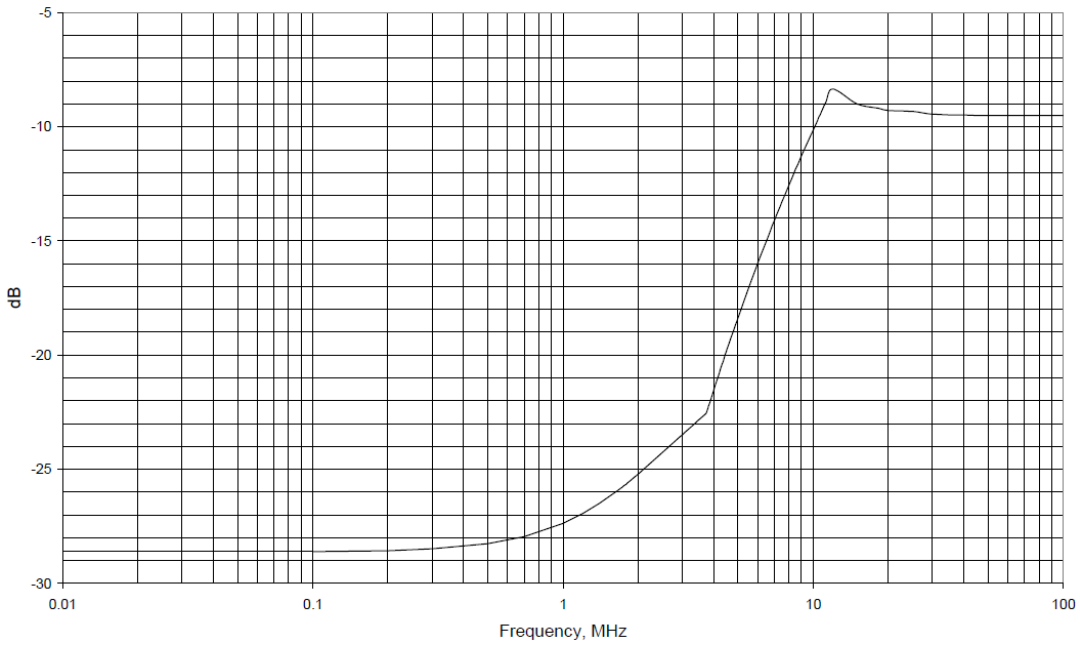


Figure 200: Conversion factor from 10 m to 30 m measurements, ETSI EN 300 330 V2.1.1, Figure H.1

In addition to the free field attenuation, the signal will also be attenuated by barriers such as wall or buildings with increased distance.

A10.6 FREQUENCY COINCIDENCE

A10.6.1 Bandwidth of victim receiver

The assumed bandwidth for comparisons is 2.7 kHz for single-sideband (SSB) voice communication and 200 Hz for CW or digimodes.

A10.6.2 Bandwidth of interfering source

The fundamental frequency of the power transfer is controlled by a quartz clock and therefore is subject to its frequency stability. IEC 61980 [7] requires a deviation of less than 50 Hz from the intended frequency. That includes all external factors such as temperatures or production tolerances. The stability of a single device during a single session will be much tighter. During measurements of two WPT-EV systems running in parallel the frequency difference between both systems was estimated to be 0.25 Hz.

WPT-EV specific emissions are emitted by the resonant coils of both primary and secondary side. Due to their resonance behaviour, all emissions are multiples of the fundamental frequency and keep their narrow band characteristic even in higher frequency ranges.

The below figure illustrates that even the WPT-EV related semiconductor switching noise is emitted as very narrow band multiples of the resonance frequency (compare narrow 85 kHz needles).

Considering a receiver bandwidth of 2.7 kHz, a maximum of ca. 4% of the available frequency band might be affected by WPT-EV specific emissions.

The widespread noise visible in the plot is not WPT-EV specific but origins from the AC input stage power factor correction that creates conducted emissions radiating from the unshielded AC cable (see 66 kHz peaks).

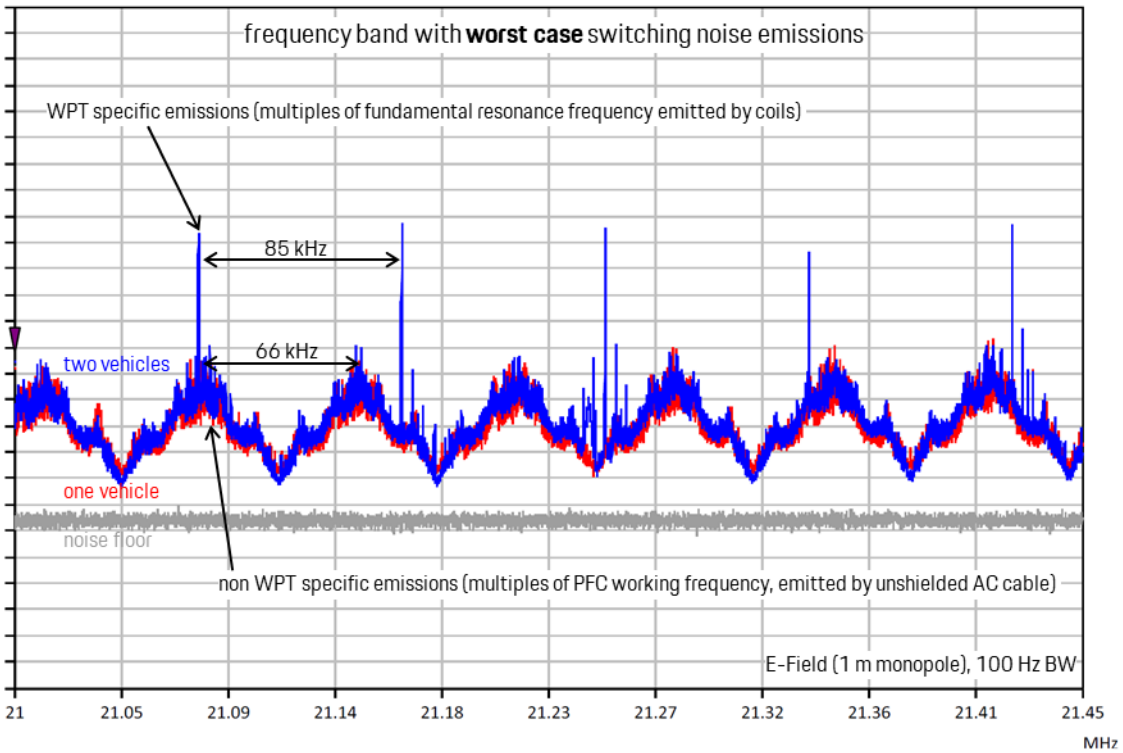


Figure 201: E-Field measurement with 100 Hz bandwidth on the frequency band with worst case switching noise emissions of this specific WPT-EV system

A10.6.3 Signal modulation

The frequency and amplitude are not modulated during a power transfer session and it is not used to transmit information.

The generated field is only used locally. Hence the industry considers WPT-EV as ISM device according to Art 1.15 of ITU-RR. The only exception being the first seconds of the session setup, where:

- some manufacturers choose to cycle through the frequency band on a low power basis in order to find the efficiency optimum;
- some manufacturers choose to use the low power excitation method where a temporary low power signal is produced to measure the coupling value between the two coils.

A10.7 SIGNAL STRENGTH COINCIDENCE

A10.7.1 Desired signal strength at the victim receiver

The victim receivers signal strength must be above ambient noise by a “desired over undesired signal ratio” to be relevant for interference estimation. Statistically the signal will be higher in most cases, as not every receiver is located in the lowest fringe of signal strength.

As WPT-EV is expected to be installed in residential areas with adjacent private parking places, it can be assumed that a significant amount of ambient noise will be present due to other high power appliances such as cooking appliances, heat pumps, EV chargers or PV-installations. Hence it can be assumed that the average signal strength still received by a victim receiver is significantly higher than in quiet rural areas.



Figure 202: Example for residential area as a likely installation place for WPT-EV, note the 16 PV-installations visible

The following plot shows the actual ambient noise emission spectrum measured in a residential environment, compared to the median value of man-made noise. An interferers signal is expected cause interference if it exceeds the ambient noise.

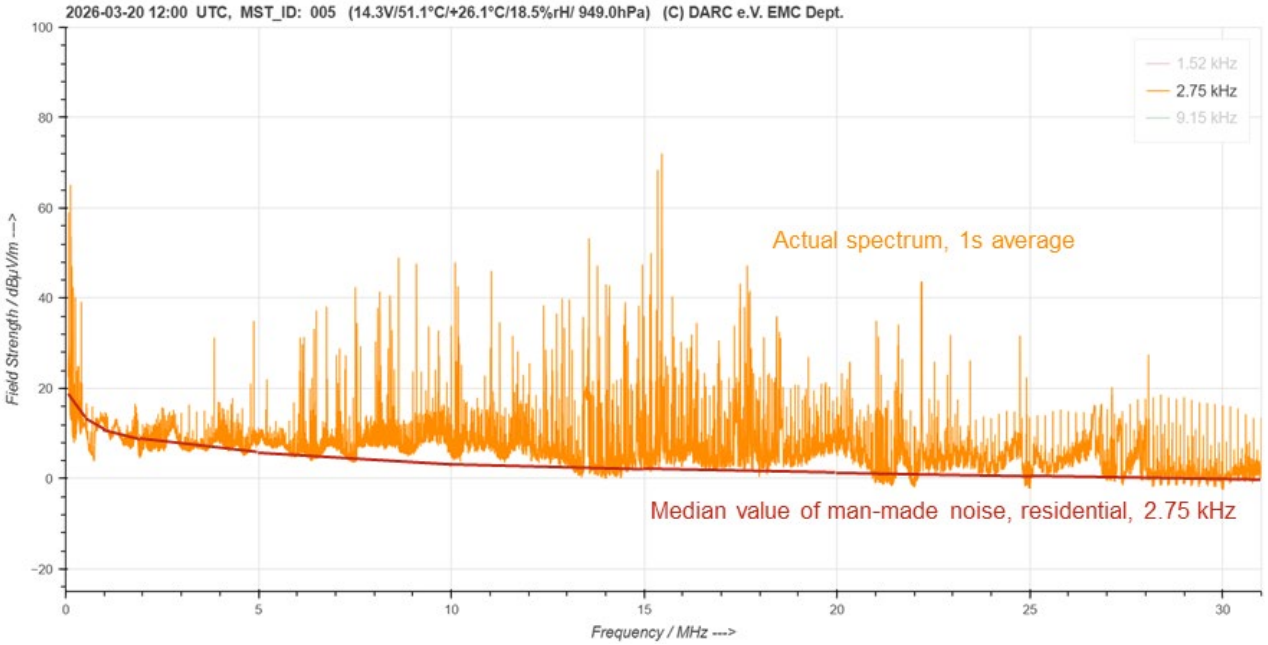


Figure 203: Ambient noise spectrum in a residential environment, Measurement by ENAMS station Ulm-005, 20.03.2026 12:00, compared to median value of man-made noise (residential, 2.75 kHz) according to Recommendation ITU-R P.372-17, table 1 and equation 7 [25]

A10.7.2 Victim receivers signal gain for interferers signal

In 10 m distance the lower frequencies of WPT-EV emissions are predominantly magnetic field due to the near field conditions. Traditional electric field antennas (dipole, monopole) are less sensitive for magnetic field than for electric field, although this is not the case for Broadcasting that generally uses ferrite rod - magnetic field antennas

With increasing frequency, the conversion from magnetic to electric field shifts from near field to far field conditions.

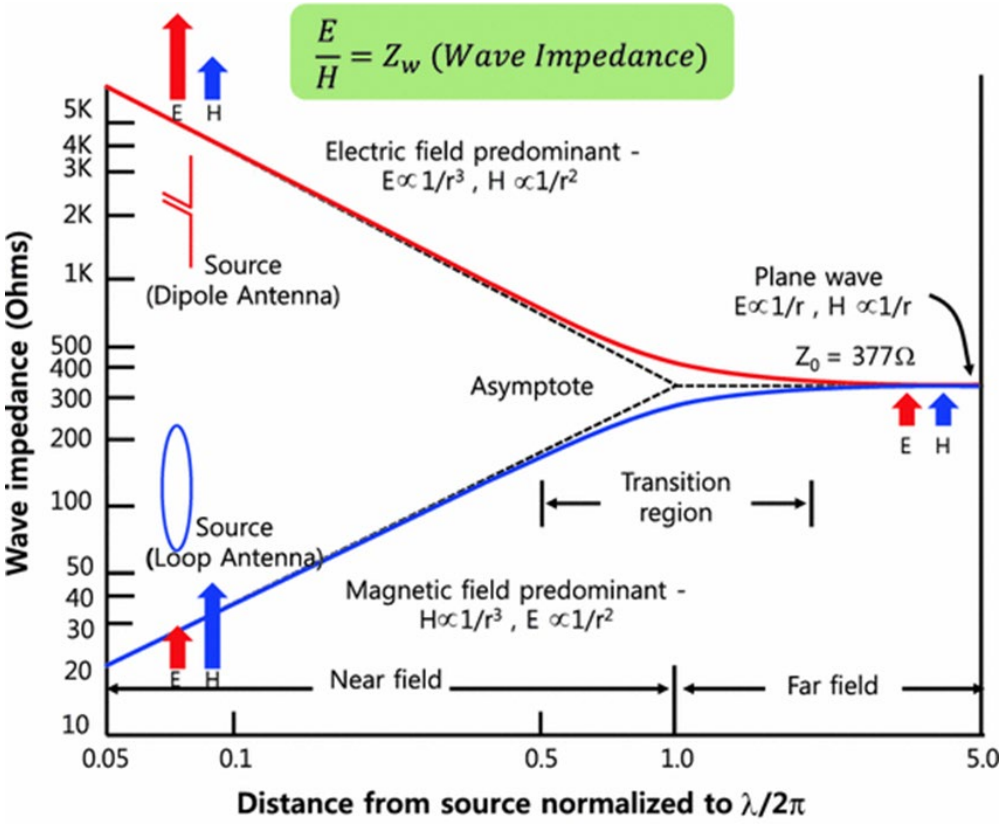


Figure 204: Diagram explaining the conversion between E-field and H-field

The below figure gives a rough estimation on the frequency ranges where the transition from near to far field occur in 10 m distance.

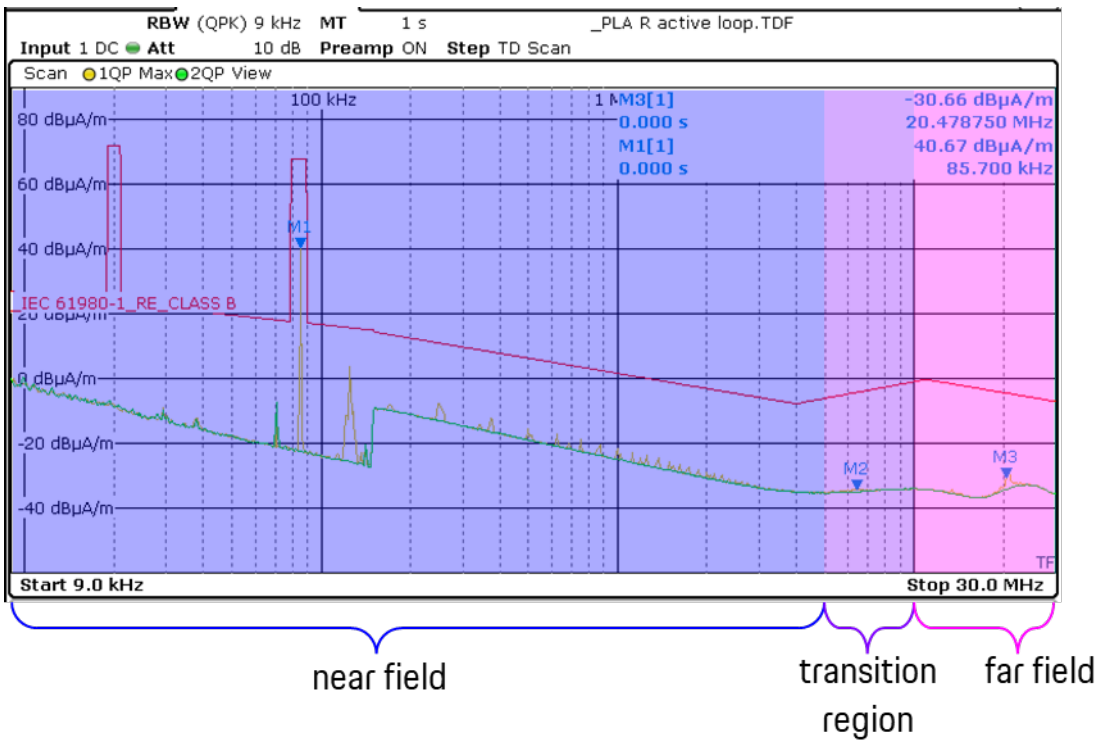


Figure 205: Estimation of near- and far field conditions in 10 m distance

A10.7.3 Interfering transmitter signal strength

Several factors influence the interfering transmitter signal strength that is received by the victim receiver.

A10.7.3.1 Frequency dependence

No certified real world system will conduct EMC emissions bordering the EMC limit in the entire spectrum. individual peaks might reach the allowed limit, but for the majority of frequencies the emissions will be significantly lower than the allowed maximum. Hence the probability of receiving unwanted emissions in the range of the allowed limit is low. The below figure shows that only a very small share of emissions comes close to the allowed limit, while the majority is far below.

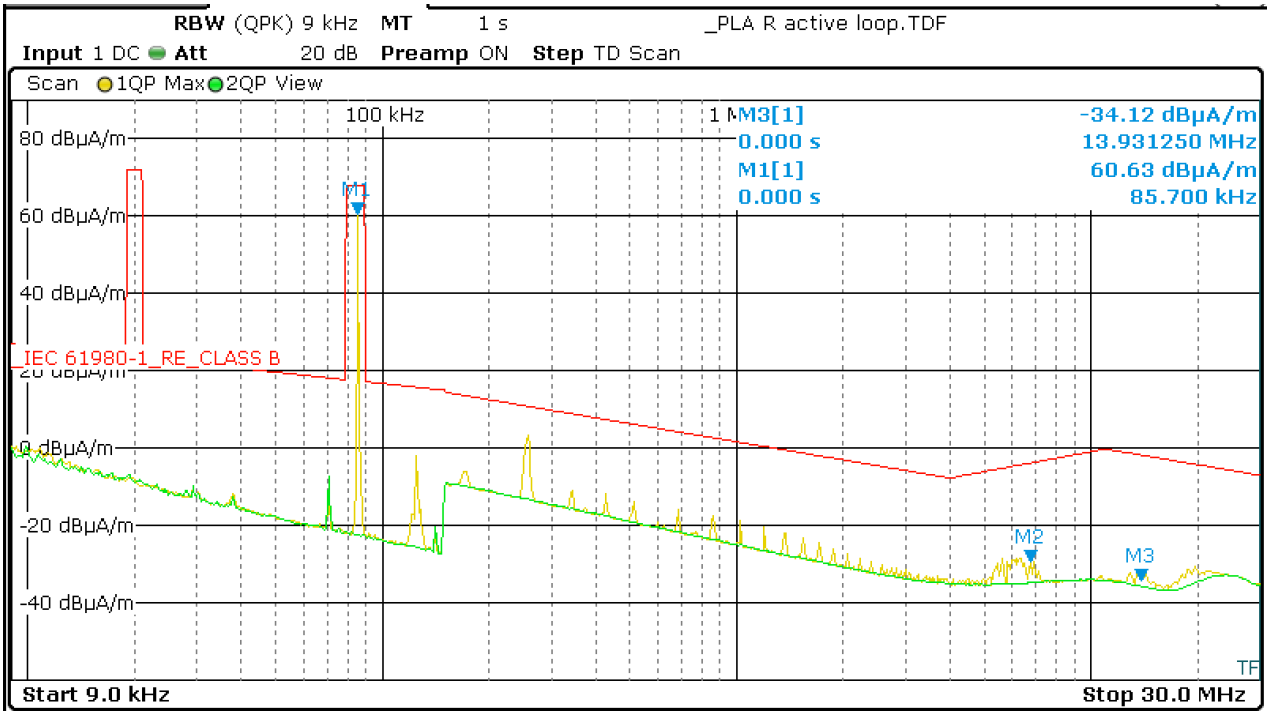


Figure 206: Emission profile of the tested WPT-EV system

A10.7.3.2 Operating power

Higher frequency emissions originated by semiconductor switching noise are influenced by the operating power. A WPT-EV system might not always run on full power and hence emit emissions lower than the worst-case profile.

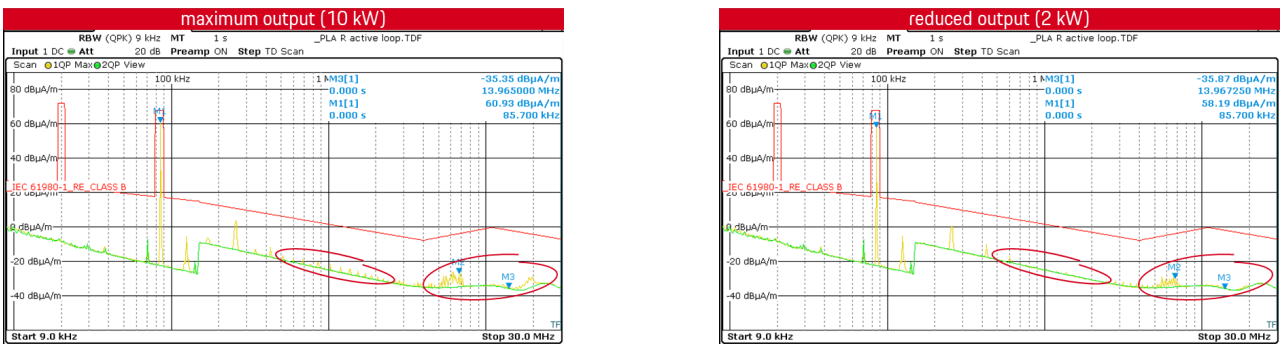


Figure 207: Comparison of emission profile for 100% and 20% output power

A10.7.3.3 Direction of emissions

WPT-EV emissions are not distributed equally but form main lobes pointing in different directions. The direction of these lobes depends on their frequency and the coupling coefficient. Lower frequencies tend to spread more to the vehicle sides while higher frequencies spread more to the vehicle front. The below figure compares both extremes.

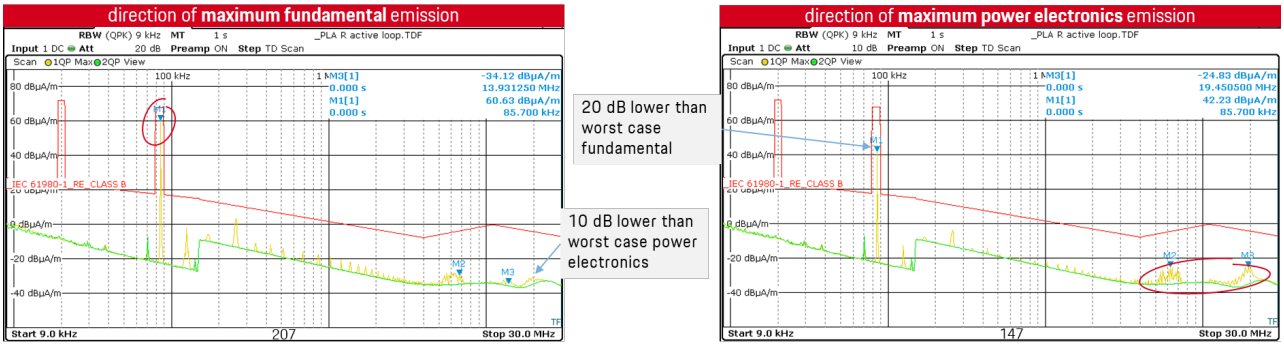


Figure 208: Comparison of measurements from two different directions, showcasing the worst-case fundamental amplitude and the worst case HF switching noise amplitude

Polar plots reveal the actual shape of the aforementioned main lobes and their different orientation.

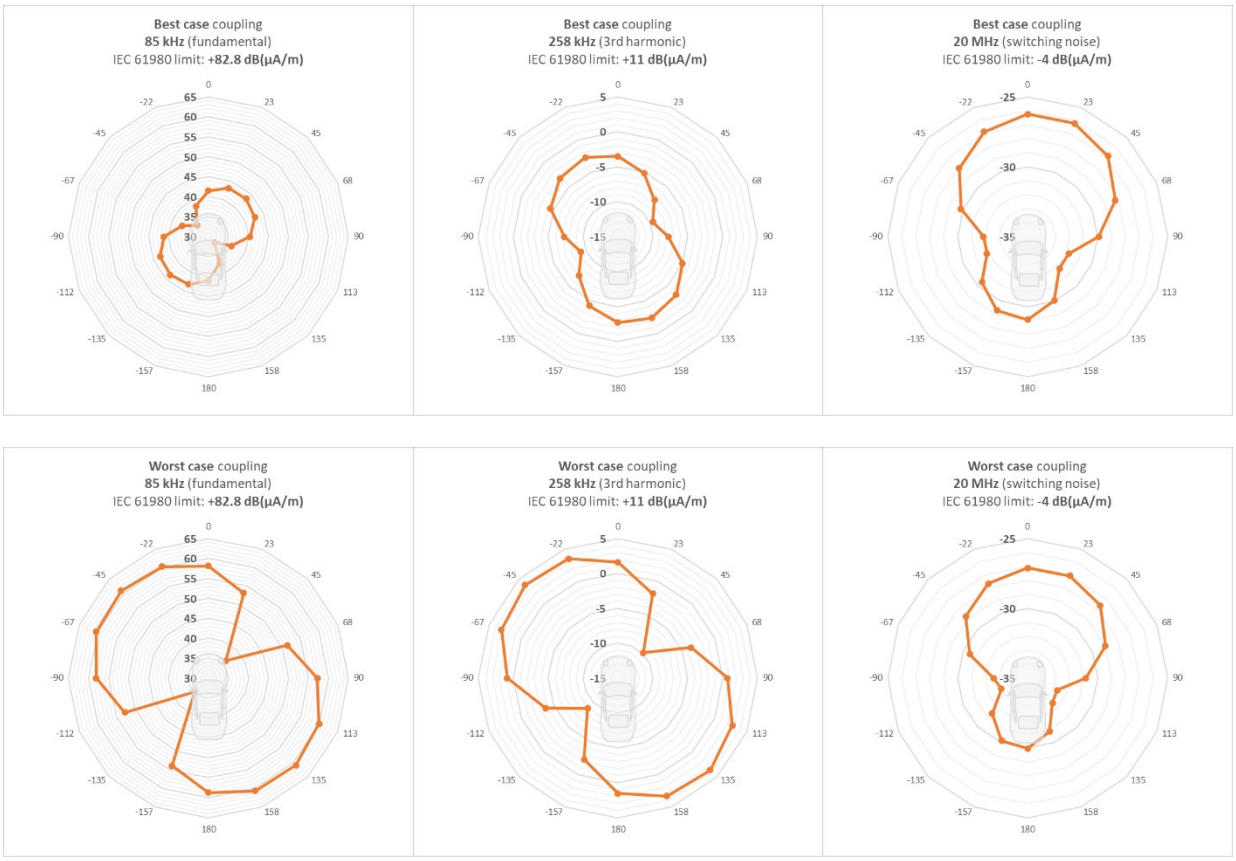


Figure 209: Polar plots of emissions of specific frequencies under worst case and best-case coupling conditions

Statistically the majority of potential victim receivers operate at a direction that receives emissions significantly below the worst case.

A10.7.3.4 Coupling coefficient of coils

The amplitude of the lower harmonics strongly depends on the coupling coefficient between primary and secondary coil. A WPT-EV system is designed to fulfil EMC requirements in worst-case conditions. As the actual offset will be randomly distributed, so will the amplitudes be distributed below the worst-case value.

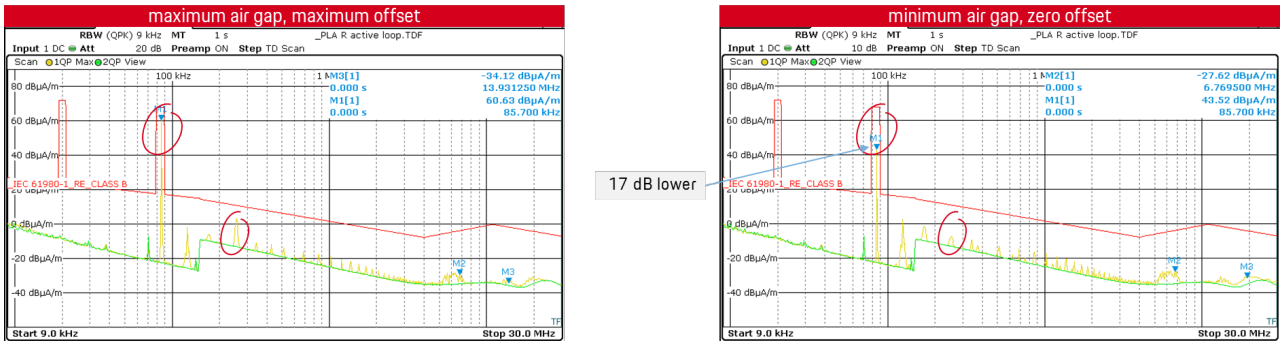


Figure 210: Comparison of emission profile for maximum and minimum coupling coefficient

A10.7.3.5 Attenuation by obstacles

Between the WPT-EV system and a victim receiver may be one or more obstacles in form of walls or other vehicles that further attenuate the emission.

In more densely populated areas, WPT-EV systems will likely be installed in underground parking areas, where its emissions will be significantly attenuated before reaching a victim receiver.



Figure 211: Example for underground parking with EV chargers example, AMAG Ladehaus Opéra in Zürich,

The below figure shows that according to National centre for charging infrastructure, Germany **Error! Reference source not found.** at least 63% of all private charging EV charging stations are located within a parking garage or underground parking place.

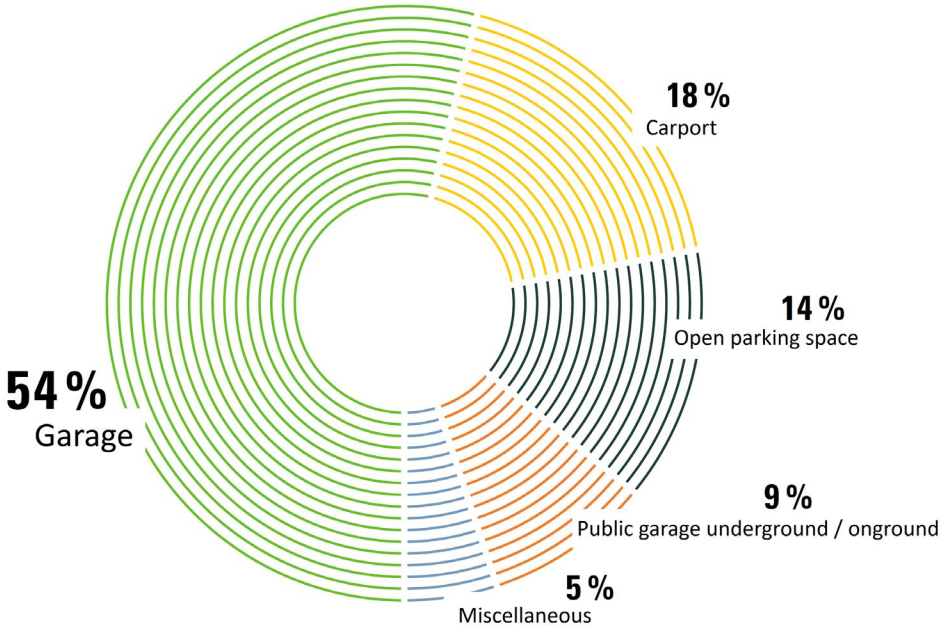


Figure 212: Location of private charging stations

A10.8 AGGREGATION OF MULTIPLE CHARGING STATIONS

Two vehicles placed next to each other with the same distance to the receiver will influence the emission spectrum in several ways:

- The HF peaks caused by switching noise will rise by about 5 dB;
- The lower frequencies will either rise or fall, depending on the orientation change of the main lobes.

The below figure shows how some peaks will rise while others fall with the second vehicle being activated.

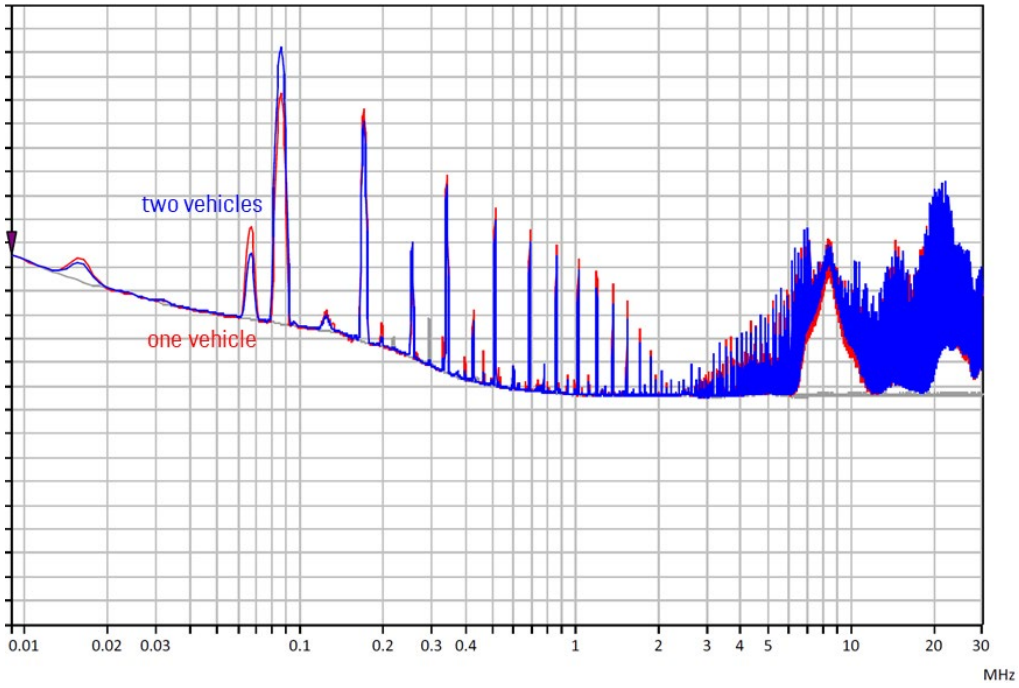


Figure 213: Comparison of one vs. two vehicles charging in parallel, measured from vehicle front

The below figure shows the assumed orientation change of the emission lobes that lead to the observed behaviour that some peaks decrease with the second vehicle being activated. In this case, the 1 MHz lobe seems to turn away from the receivers perspective and hence reduces in amplitude.

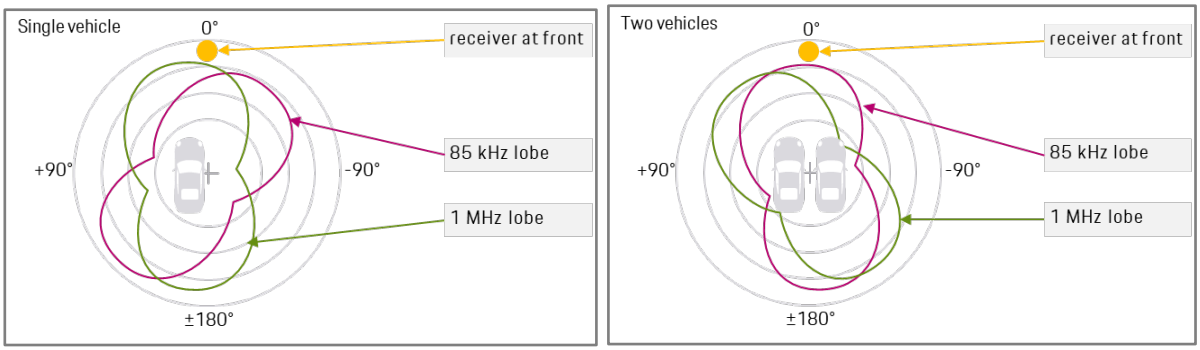


Figure 214: Assumed orientation change of the emission lobes

A10.9 WPT EMISSIONS VS. AMBIENT NOISE

The below figure showcases an example of real WPT emissions compared to a real world ambient noise measurement by an ENAMS station. For this comparison the station Ulm-005, time 20.03.2026 12:00, located in a residential environment is chosen. In many cases the WPT-EV emissions will be covered by the ambient noise.

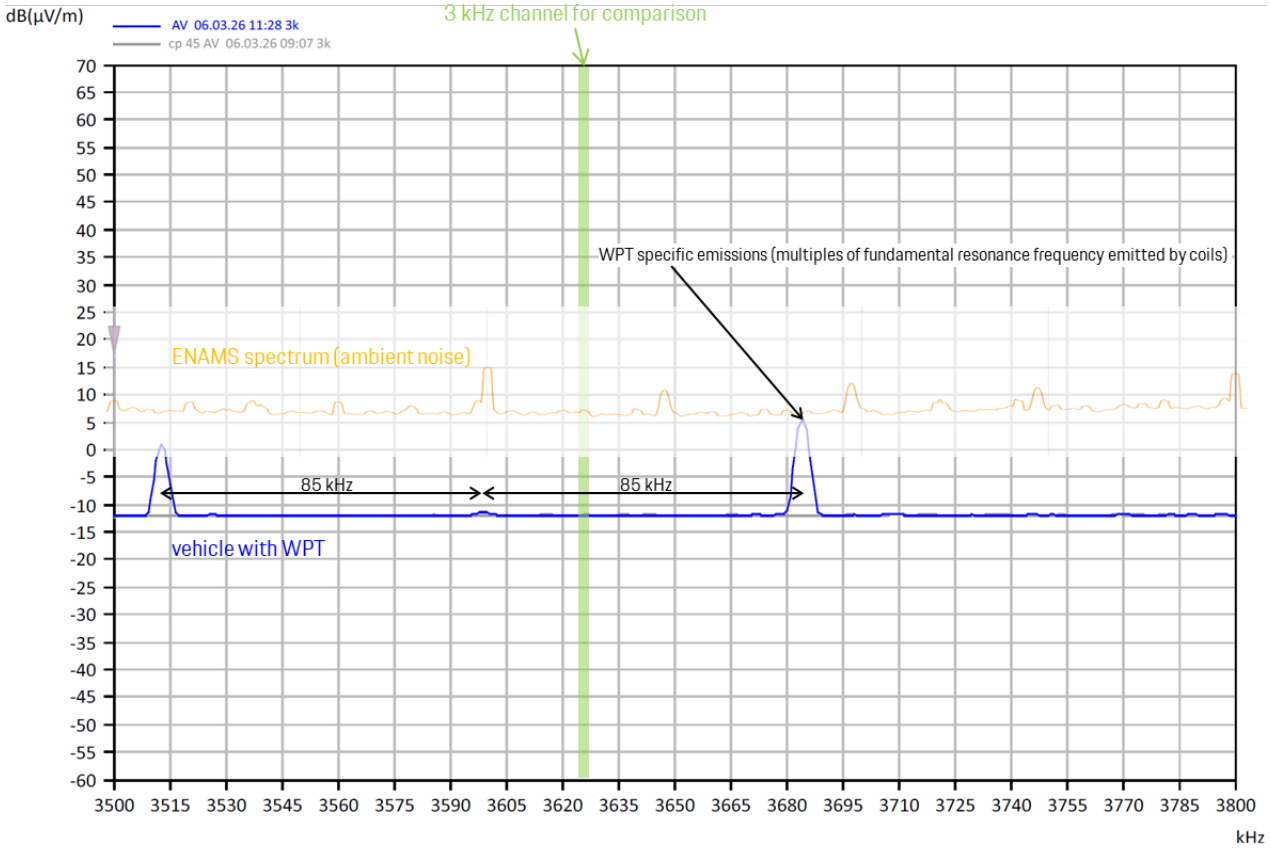


Figure 215: WPT emissions in direct comparison to measured ambient noise

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