CEPT ECC
Electronic Communications Committee

Addendum to ECC Report 333

Non-beam WPT applications, excluding WPT-EV, operating at frequencies below 30 MHz and transmitting at power levels above 30 Watts

approved 23 May 2025

0 EXECUTIVE SUMMARY

This Addendum to ECC Report 333 [2] evaluates compatibility between higher power (>30 W) non-beam inductive Wireless Power Transmission (WPT) in various frequency bands below 30 MHz and radiocommunication services. It was developed based on the information received from ETSI Technical Committee (TC) ERM (EMC and Radio Spectrum Matters) and other contributions.

ECC Report 333 included studies on low-power (< 30 W) inductive WPT, although some of those studies are also applicable to higher power (> 30 W) non-beam WPT applications. References have been given, where applicable, to the relevant studies in ECC Report 333.

ECC Report 333 [2] and this Addendum do not cover WPT-EV, which is covered by ECC Report 289 [35].

Conclusions from the study of radiocommunications services for higher power WPT are provided below.

Maritime service

Depending on the Maritime System, environmental conditions and assumed emission values, the range of calculated separation distances varies between 4 m and 850 m. Even if no distance was found in literature that could be regarded as acceptable, it can be assumed for inland shipping that distances below 50 m should be reached. Considering MF/HF maritime receivers which are compliant with minimum requirements (low performing receivers) and considering WPT emission values of -15 dBµA/m, separation distances in a range of 104 m – 660 m are required. For the same receiver characteristics and WPT emission values of -35 dBµA/m, separation distances in a range of 31 m – 67 m are required.

Broadcasting service

For the Broadcasting Service, the following parts of ECC Report 333 are also applicable for higher power inductive WPT:

- ECC Report 333, executive summary
- ECC Report 333, annex 3: Detailed information on the protection of the Broadcasting Service from generic WPT;
- ECC Report 333, annex 4: Performance of an MF AM sound broadcasting receiver in the presence of interference from WPT;
- ECC Report 333, annex 9: Practical Coexistence measurements of WPT and AM receiver.

Amateur service

For the Amateur Service, the following parts of ECC Report 333 are also applicable for higher power inductive WPT:

- ECC Report 333, annex 1: Studies into Impact of WPT Emissions on the Amateur Service

In addition to the findings of ECC Report 333, material received while developing this addendum suggested that, taking into account additional mitigations, the same level of unwanted emissions from WPT as in Table 1 of ECC Report 333 for the Broadcasting Service, could also be sufficient to prevent interference to the Amateur Service.

Aeronautical Radionavigation

For the Aeronautical Radionavigation Service, the following part of ECC Report 333 is also applicable for higher power inductive WPT:

- ECC Report 333, annex 10: Impact Study of Non-Beam Inductive WPT Applications in 300–400 kHz on the Aeronautical Radionavigation Service

STFS Service

For the STFS Service, the following part of ECC Report 333 is also applicable for higher power inductive WPT:

- ECC Report 333, section 3.7: Standard Frequency and Time Signal Service

Fixed and Mobile Services

For the Mobile Service, the following part of ECC Report 333 is also applicable for higher power inductive WPT:

- ECC Report 333, section 4.8: Impact on the Fixed and Mobile Services Below 30 MHz (Minimum Coupling Loss).

Radio Astronomy service

Studies on the protection of radio astronomy observations have proposed several investigations on spurious emissions from WPT systems affecting the RAS bands. LOFAR stations, which are mainly located in the Netherlands, with international stations in several other CEPT countries, are sensitive to all emissions which fall within their operating range of 10 MHz to 90 MHz and 110 MHz to 240 MHz. The studies, based on the Recommendation ITU-R SM.2028-0 propagation model, indicate that the calculated separation distances are up to 14.0 km assuming that the WPT emission levels were at the maximum levels specified in ETSI EN 303 417 [22], 48 km for CISPR 11 [23] (Group 2, Class A), and 8.6 km for CISPR 14 [24]. If the spurious emissions from the WPT are below -35 dBµA/m, a minimum separation distance of 2.3 km is required. Conversely, if the emissions reach -20 dBµA/m, the required separation distance increases to 5.4 km. Additionally, the study given in chapter 4.3.2 in this Addendum of spurious emissions above 30 MHz up to 1 GHz produced a calculated separation distance of up to 28.2 km.

Cordless Kitchen WPT applications

Based on simulations and tests conducted on prototype kitchen devices, these WPT systems are multi-frequency systems with necessary harmonic frequency components within the frequency range 20-148.5 kHz. The generated spectrum closely resembles the spectrum generated by existing induction cooking systems, of which there are already hundreds of millions in the market.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
ADF	Automatic direction finding
AGV	Auto guided vehicle
AIMD	Active implantable medical device
AM	Amplitude modulation
CEPT	European Conference of Postal and Telecommunications Administrations
CISPR	International Special Committee on Radio Interference
DGNSS	Differential global navigation satellite system
DSC	Digital selective calling
ERIC	European Research Infrastructure Consortium
ECA	European common allocation table (ERC Report 25)
ECC	Electronic Communications Committee
EMC	Electromagnetic compatibility
ERC	European Radiocommunications Committee
ERP	Effective radiated power
ETSI	European Telecommunications Standards Institute
FSK	Frequency shift keying
GMDSS	Global maritime distress and safety system
HBA	High-Band Antenna array
ICAO	International Civil Aviation Organization
IN	Impulse noise
ITU-R	International Telecommunication Union-Radio sector
LBA	Low-Band Antenna array
LEV	Light electric vehicle
LOFAR	Low frequency array
NAVDAT	Navigational data
NAVTEX	Navigational telex
NDB	Non-directional radio beacon
OBW	Occupied bandwidth

RAS	Radio astronomy service
SFTS	Standard frequency and time signal service
SNR	Signal to noise ratio
SRdoc	System reference document
TR	Technical report
Tx	Transmitter
WPC	Wireless Power Consortium
WPT	Wireless Power Transmission
WPT-EV	Wireless Power Transmission for Electric Vehicles

1 INTRODUCTION

Wireless Power Transmission (WPT) systems which are studied in this Addendum, are devices that enable the transmission of electrical energy without physical connections, using methods such as electromagnetic induction or resonance coupling.

This Addendum provides the result of the studies examining the compatibility between the various types of higher power WPT and the incumbent radiocommunication services/systems using the same or adjacent frequency bands below 30 MHz.

It has been developed using information given in the ETSI TR 103 493 [1] and subsequent information received from ETSI Technical Committee (TC) ERM (EMC and Radio Spectrum Matters), and other contributions.

ECC Report 333 is described as applicable to low-power (< 30 W) WPT. Nevertheless, much of the content of that report is equally applicable to higher power (higher power means medium and high power in terms of this addendum) WPT considered in this addendum. Where this is the case, it is stated in the text of this Addendum.

Wireless charging is being adopted and developed for application areas such as tablets, laptops, power tools, home and garden appliances, medical/surgical tools, industrial products, eBikes, drones, robots and wearable electronics such as smart watches or fitness trackers.

ECC Report 333 [2] and this Addendum do not cover WPT-EV, which is covered by ECC Report 289 [30].

2 SYSTEM CHARACTERISTICS OF NON-BEAM INDUCTIVE AND AIMD WPT

2.1 OVERVIEW

Generic non-beam inductive WPT applications are used to charge or power various devices including mobile phones, tablets, laptops, power tools, kitchen appliances, autonomous vehicles, industrial devices, implantable medical devices. The studies provided in this Addendum cover the compatibility of the higher power devices with radiocommunications services which are allocated frequencies below 30 MHz. In this section, the technical specifications and use cases of various WPT systems, studied in this Addendum, are provided.

2.2 APPLICATIONS AND USE CASES

2.2.1 Laptop / tablets

Laptop and tablet computers typically require between 30 and 200 W while charging.

2.2.2 Industrial wireless applications

Applications include unmanned robotic equipment such as robotic arms used in heavy manufacturing, drones used to monitor gas pipelines and electric towers and auto-guided vehicles (AGVs) used in logistics.

Power requirements between 30 and 3000 W depending on the application. A drone battery, for instance, generally needs 60 W to power up;;, while a service robot needs about 200 W when charging. Kilowatt power levels are needed to charge an AGV. In some applications, with no-embedded battery, wireless power can also be delivered to drive the motor.

2.2.3 Light Electric vehicles

Light Electric Vehicles (LEV) include e-scooters, e-bikes, e-rickshaws, e-forklifts, e-motorbikes and low speed electric vehicles.

2.2.4 Cordless Kitchen applications

These include stand-alone wireless power units and dual function induction cooktops that wirelessly deliver up to 2200 W of power to cordless kitchen appliances. Applications include, small domestic appliances, such as rice cookers, toasters, blenders, coffee makers and airfryers. They are powered by placing them on enabled induction cooktops or wireless power units installed beneath a standard non-metallic countertop or table.

2.2.5 Usage parameters

The following table provides the information on potential usage of higher power WPT applications.

Table 1: Potential usage of higher power WPT applications

Application	How and where are the devices used" (at home only, indoor outdoor, mobile, in hospitals only etc).	How long are the devices already in the market	Number of devices currently in the market (EU and worldwide)	Number of devices estimated for 2025, 2030 in the market (Europe and worldwide)	Used harmonised standard for conformity assessment	Frequency range of emission Magnetic field at 10 m
Medium power Examples: Laptop charging, e-scooter, e-bike, drones	Domestic environments. Household robots. Laptop, e-scooter and e-bike charging. Industrial applications e.g. automated guided vehicles in warehouses. A small proportion may also be used outdoors for applications such as charging drones. Examples of potential usage: Home use – few hours/month Industrial/factory 2-16 hrs/day.	Standardised medium power applications are in the early stages of development. Industrial process applications have been in use for many years in a range of applications.	No standardised applications are deployed at present; however, many different types of devices are in use in industrial process automation.	Medium power applications are at an early stage of market development and deployment data is not yet available. A working assumption could be used. For example, 5% market penetration by 2025. 20% market penetration by 2030.		20-148.5 kHz 72 - 42 dBµA/m Current emission levels defined in ERC Recommendation. 70-03, annex 9 [5] for the frequency range 20-148.5 kHz provide sufficient level for operation.
High Power Cordless Kitchen appliances with up to 2.2 kW transferred power	Majority in domestic environments; some in commercial environments such as restaurant kitchens. Some may be used outdoor (e.g. barbeque) applications. Depending on market adoption, typically 3-4 wireless power points inside a kitchen. Activity: Cooking 30 min -1 hr Kitchen machines: 20 minutes - 1 hr.	A Cordless Kitchen specification is under development and is not yet commercially available in Europe. One technology is based on induction heating technology which was invented in the 1930s and moved to mass adoption in the 1980s. Induction heating using magnetic coupling is well-established. No harmful interference with existing radiocommunication services from induction cookers is recorded.	Cordless Kitchen applications are under development and had not generally been deployed in Europe. A limited number have been deployed in China.	The Wireless Power Consortium estimates that the European market for devices (e.g. integrated in induction hobs and standalone Tx devices) is in the region of 360 k by 2025 25.5 m by 2030. (Source SAR Insight)		20-148.5 kHz 72 - 42 dBµA/m Current emission levels defined in ERC Recommendation 70-03, annex 9 [5] for the frequency range 20-148.5 kHz provide sufficient level for operation.

2.2.6 Power classes given in ETSI SRdoc TR 103 493

2.2.6.1 Introduction

This chapter summarises the information on the power levels given in ETSI SRdoc TR 103 493 [1] (WPT systems operating below 30 MHz).

2.2.6.2 ETSI system reference document TR 103 493

WPT systems are used/planned for usage within a lot of different scenarios. The categorisation of WPT could therefore also be possible over the "power", transmitted by the WPT.

2.2.6.3 Power Classes (Chapter 7.1.2 of SRdoc relevant for the applications covered by this Addendum)

The following power classes, describing the maximum transferred energy/power, were foreseen with different WPT specifications. The distinction in power classes, instead of frequencies was used in the present document to consider the variety of use-case, size of the device, etc.

Low power WPT and its corresponding applications were already studied within CEPT. ECC Report 333 [2] (Non-beam Wireless Power Transmission (WPT) applications other than WPT-EV operating in various frequency bands below 30 MHz) provides the details of such applications.

Low-power WPT applications (below 30 W) are covered by ECC Report 333, while higher power WPT applications (> 30 W) are categorised in Table 2 which summarises the applications, the power and the frequency bands used currently according to ETSI TR 103 493 relevant for the applications covered by this Addendum.

Table 2: WPT classification (WPT-EV excluded)

Applications	Power Class	WPT Frequency band	Magnetic field limit at 10 m
Power tools, laptops, lighting, household devices, furniture, television, robots, healthcare, e-bikes, industrial applications etc.	50 W < P < 200 W	90-119 kHz	42 dBµA/m
		119-135 kHz	42 dBµA/m
		135-140 kHz	42 dBµA/m
		140-148.5 kHz	37.7 dBµA
		148.5-205 kHz	-15 dBµA/m (Note 1)
Kitchen appliances (blender, rice-cooker, fryer, mixer), lighting, kitchen countertops	P < 2.4 kW	20-79 kHz	42 dBµA/m
NOTE 1: The maximum allowed total field strength is -5 dBµA/m at 10 m for systems operating at bandwidths larger than 10 kHz whilst keeping the density limit (-15 dBµA/m in a bandwidth of 10 kHz).			

3 SYSTEM CHARACTERISTICS OF RADIOCOMMUNICATION SERVICES OPERATING IN THE FREQUENCY BANDS BELOW 30 MHZ

3.1 AMATEUR SERVICE

ECC Report 333, section 3.2 describes the operational characteristics of the amateur service in relevant parts of the radio spectrum.

3.2 BROADCASTING SERVICE (SOUND)

ECC Report 333, section 3.2 describes the operational characteristics of the broadcasting service in relevant parts of the radio spectrum. The following frequency bands are allocated to the Broadcasting Service (Sound) on a primary basis through the ITU Radio Regulations:

- 148.5-283.5 kHz Band 5 (LF);
- 526.5-1606.5 kHz Band 6 (MF);
- 3.2-26.1 MHz Band 7 (HF).

3.3 RADIOCOMMUNICATION SERVICES AT 5 MHZ AND 6.78 MHZ

Incumbent services/systems in 5 MHz range are the broadcast, fixed/land mobile and space research services. The Standard Frequency and Time Signal Service is also present. A summary of the relevant spectrum use is included in ECC Report 333, section 3.4.

3.4 MARITIME SERVICE

3.4.1 NAVTEX (Navigation telex)

This 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 Radio Regulations.

3.4.2 DSC (Digital selective calling)

This 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 Radio Regulations.

3.5 AERONAUTICAL RADIONAVIGATION SERVICE IN 255-535 KHZ

ECC Report 333, section 5 provides the specifications of ADF and NDB in the aeronautical service.

3.6 MOBILE AND FIXED SERVICES BELOW 30 MHZ

Mobile and Fixed allocations, including military and aeronautical use from 2 to 30 MHz are described in ECC Report 333, section 3.6.

3.6.1 Military

Military applications are used in the Mobile and Fixed allocations below 30 MHz. These applications are listed in ECC Report 333, table 8 and are further discussed in ECC Report 333, section 3.6.1.

3.6.2 Civil Aviation

Civil aviation HF communications are part of the AM(R)S and operate in portions of the frequency band 2.850 - 22 MHz. This usage is described in ECC Report 333, section 3.6.2.

3.7 STANDARD FREQUENCY AND TIME SIGNAL SERVICE

This service is described in ECC Report 333, section 3.7.

3.8 RADIO ASTRONOMY SERVICE

3.8.1 Radio astronomy in the lower part of the spectrum

The Low-Frequency Array (LOFAR) telescope (www.lofar.org and www.lofar.eu), mainly situated in the Netherlands , is an extensive pan-European network. LOFAR is used for exploration of cosmic phenomena, including cosmic rays, black holes, and the primordial universe. LOFAR uses large number of antennas (about 70000) distributed across Europe and operates at radio frequencies from 10 to 90 MHz low-band antennas (LBA) and 110 to 240 MHz High-band antennas (HBA).

LOFAR, a network of 52 stations, uses a distributed architecture to achieve high resolution and sensitivity for cosmic observations. It is part of the European Research Infrastructure Consortium (ERIC), established by the European Commission in December 2023 by Decision No. 2023/2881. For further information see LOFAR white paper 2023 [42]



Figure 1: Geographical distribution of the existing LOFAR stations in Europe (Source: ASTRON)

NenuFAR, located in Nançay, France, is a 2000 antenna phased array telescope, operating from 10 to 85 MHz. It operates both independently and as part of the LOFAR network. The Nançay site also hosts the Nançay Decameter Array (NDA), which consists of 144 helical antennas covering 10-120 MHz. The list of main current radio telescopes in CEPT countries that utilize frequencies under study is provided in the below table (this table is not to be considered exhaustive). Stations in The Netherlands are listed in Annex 1.

Table 3: CEPT countries with LOFAR stations

Observatory	Name	Country	Latitude (N)	Longitude (E)
LOFAR, core stations, Exloo	CSxx (24 core stations, see Annex 1)	Netherlands	52°54'32"	6°52'08"
LOFAR, remote stations (distributed)	RSxx (14 remote stations, see Annex 1)		see Annex 1	
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"

3.8.2 Frequency use by RAS and regulatory status below 30 MHz

Below 30 MHz, the RAS bands considered in this study are sourced from the ERC Report 25 (ECA table) [4], as shown in Table 4.

Table 4: RAS frequency allocation and usage

RAS frequency bands	Allocation status	Type of RAS Observation
13.360-13.410 MHz	Primary	Continuum
25.550-25.670 MHz	Primary	Continuum

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4 STUDIES

4.1 MARITIME SERVICE

4.1.1 Study A: Impact of "unwanted emissions of WPT" on the Maritime Service

4.1.1.1 Methodology

In this study 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/2pi.

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, table 6, Reference number 2.1.3 (Short range inductive devices operating below 30 MHz) [13] is used. The units are given in dBµA/m at 10 m distance in 10 kHz. A sensitivity analysis is done for emission levels 10 dB, 20 dB and 30 dB below the maximum value allowed according to ERC Recommendation 74-01.

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 [13].

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 [11] (formulas on page 7). This is based on ideal models of magnetic loops. Therefore, additional measurements could be conducted to confirm this model propagation effect for this use case.

4.1.1.2 Study between WPT and DGNSS @ 300 kHz

Differential GNSS systems are used to enable more accurate maritime navigation compared to GNSS systems only, and they are used in coastal, estuary and harbour areas as well as on inland waterways.

According to Recommendation ITU-R M.823-3 [15] 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 [13]. For the receiving bandwidth of 0.5 kHz this value is calculated to -1.3 dBµA/m @10 m in 0.5 kHz.

Figure 2 shows the roll-off function of the H-field that is assumed in the near field region, following a drop of 60 dB/decade [5]. The calculation is based on ERC Report 69 [11]. 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.

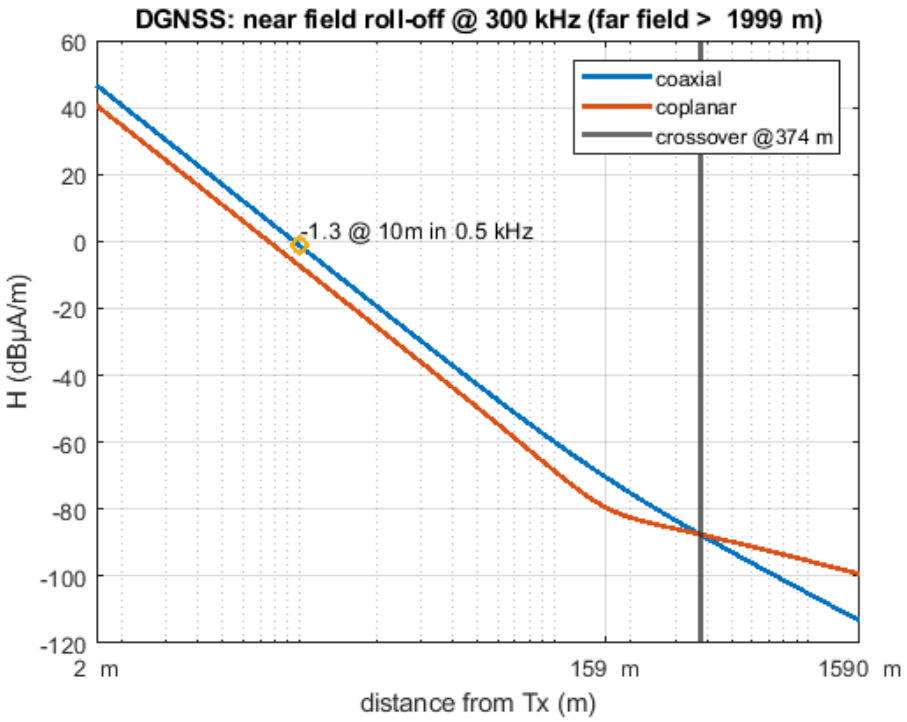


Figure 2: Roll-off function of H field at 300 kHz

According to Recommendation ITU-R M.823-3 [15] the DGNSS dynamic range is given as an 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 Recommendation ITU-R RA.769 [20] , limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 3.

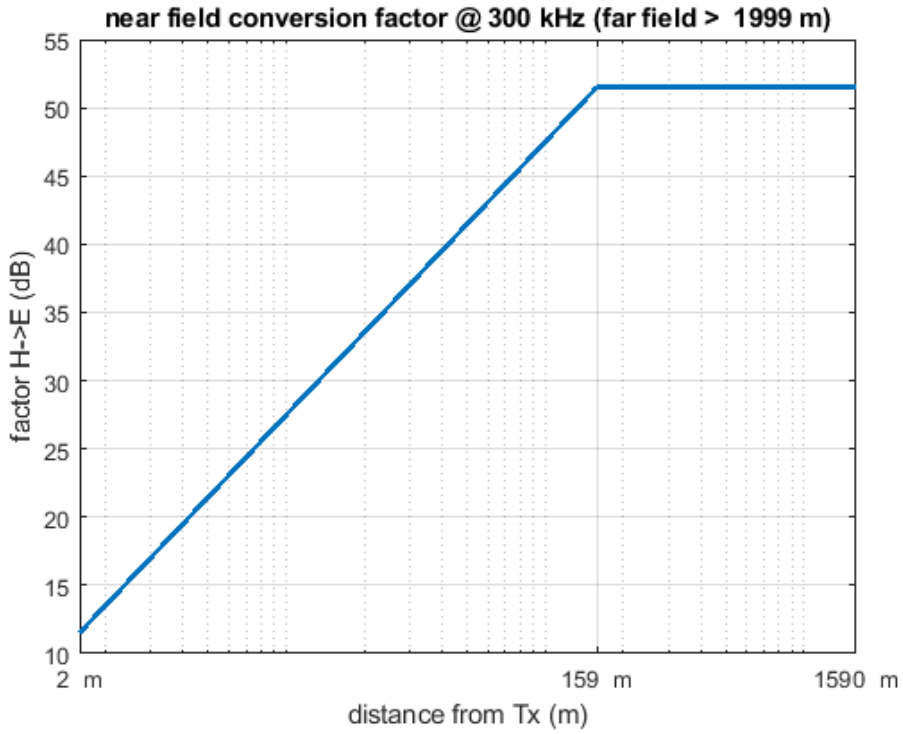


Figure 3: Near field conversion factor between H and E field

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 for this study.

Figure 4 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 [12]. 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.

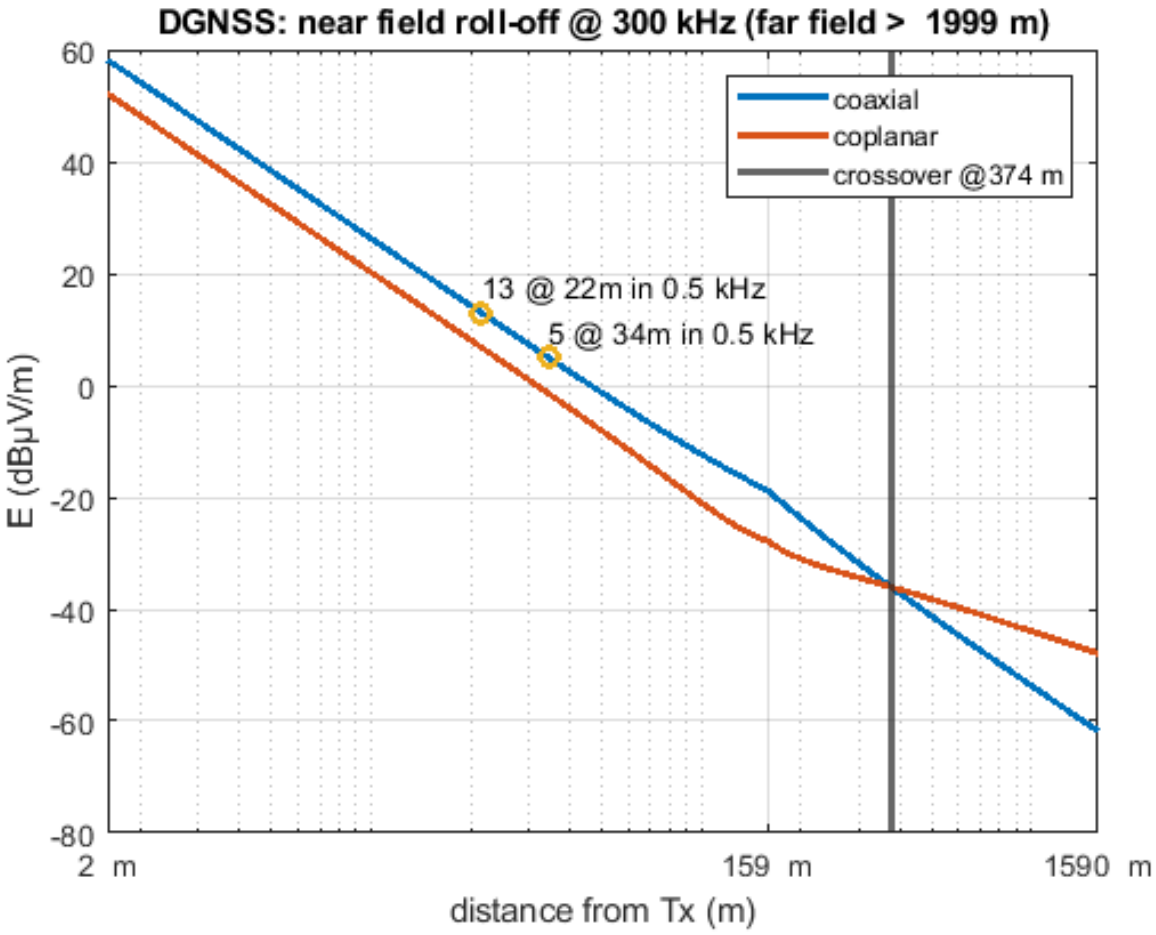


Figure 4: Roll-off function of E field at 300 kHz

4.1.1.3 Study between WPT and NAVDAT @ 500 kHz

According to Recommendation ITU-R M.2010-2 [16] 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 [13].

Figure 5 shows the roll-off function of the H-field that is assumed in the near field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [11]. 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.

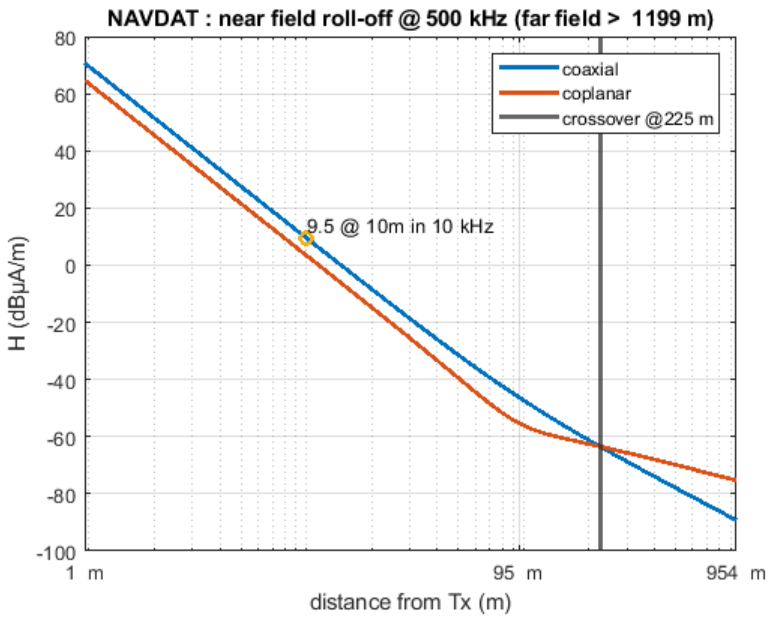


Figure 5: Roll-off function of H field at 500 kHz

According to Recommendation ITU-R M.2010-2 [16] the NAVDAT's sensitivity is given as E 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 [14], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 6.

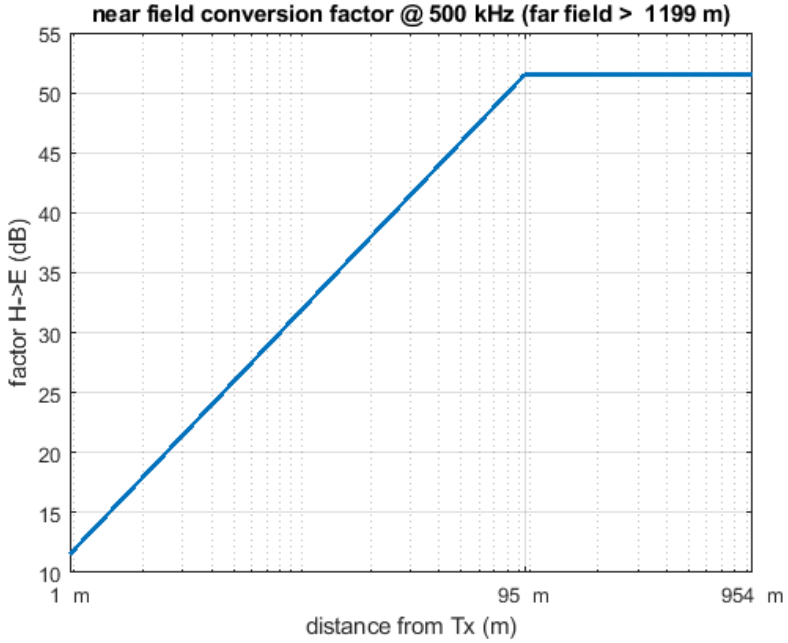


Figure 6: Near field conversion factor between H and E field

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 7 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 [12]. 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.

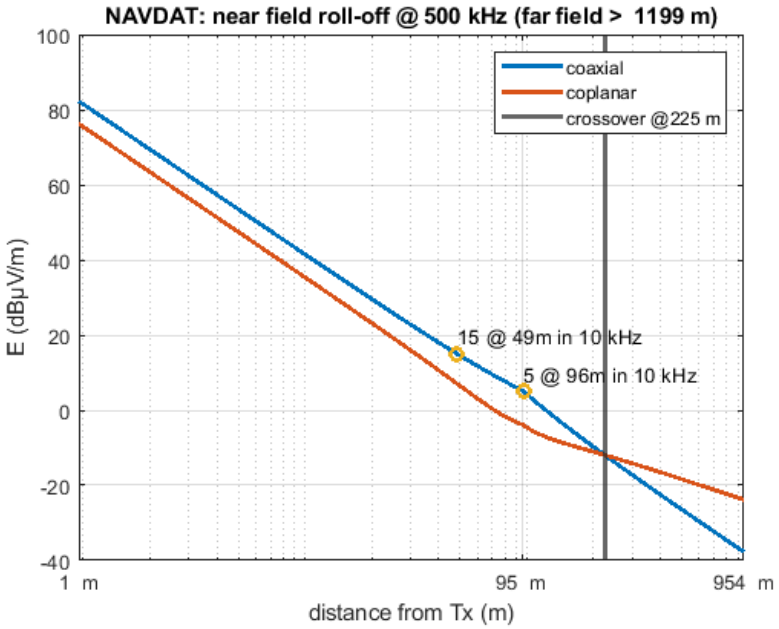


Figure 7: Roll-off function of E field at 500 kHz

4.1.1.4 Study between WPT and NAVTEX @ 500 kHz

According to MSC.508 (105) [17], 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 @10 m in 10 kHz, according to ERC Recommendation 74-01 [13].

Figure 8 shows the roll-off function of the H field that is assumed in the near field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [11]. 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.

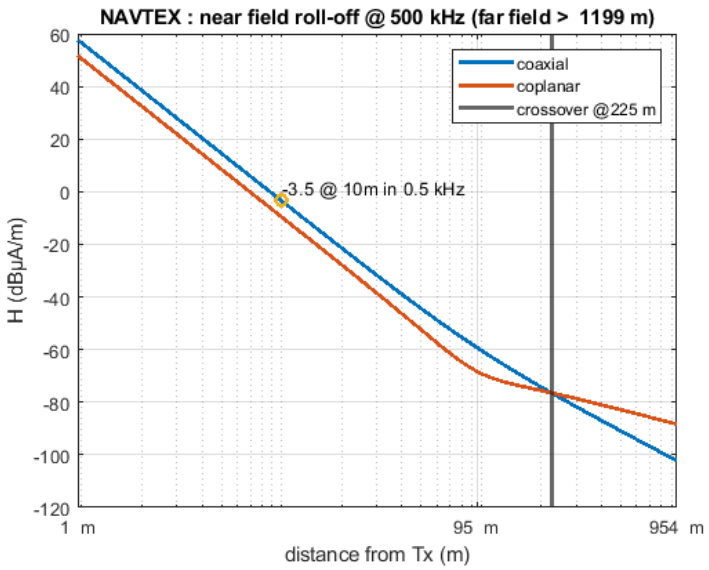


Figure 8: Roll-off function of H field at 500 kHz

According to MSC.508 (105) [17], the NAVTEX's sensitivity is given as E field of 2 µV/m. The bandwidth of 0.5 kHz is given in Recommendation ITU-R M.1467 [33]. 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 [14], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 9.

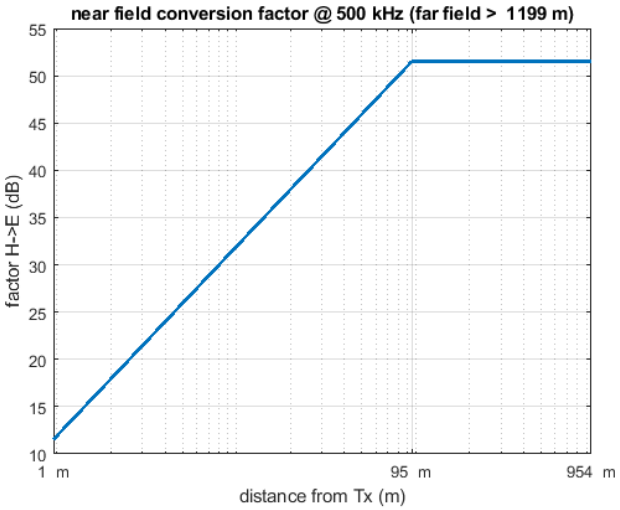


Figure 9: Near field conversion factor between H and E field

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 10 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 [12]. 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.

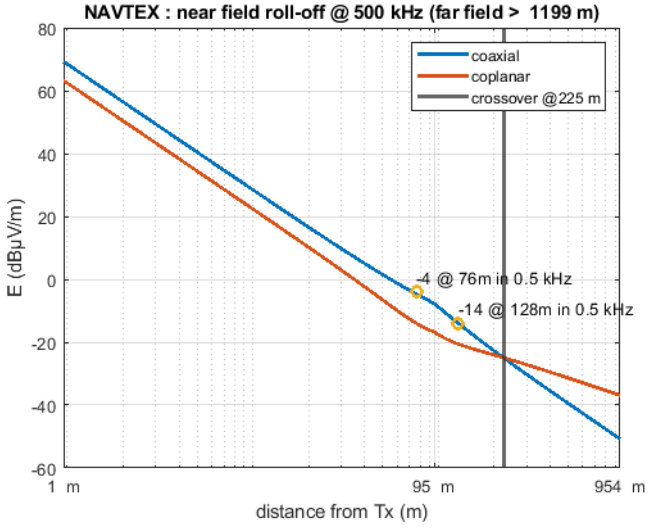


Figure 10: Roll-off function of H at 500 kHz

4.1.1.5 Study between WPT and MF voice @ 2182 kHz

According to MSC.512 (105) [18], MF Voice systems are deployed in the frequency range 1605 kHz to 4000 kHz.

This study assumes unwanted emissions from WPT systems at the frequency of 2182 kHz at a field strength of ~ 3.1 dBµA/m @10 m in 10 kHz, according to ERC Recommendation 74-01 [13]. For the receiving bandwidth of 3 kHz this value is calculated to -2.1 dBµA/m @10 m in 3 kHz.

Figure 11 shows the roll-off function of the H-field that is assumed in the near field region, following a drop of 60 dB/decade. It is based on ERC Report 69 [11]. 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.

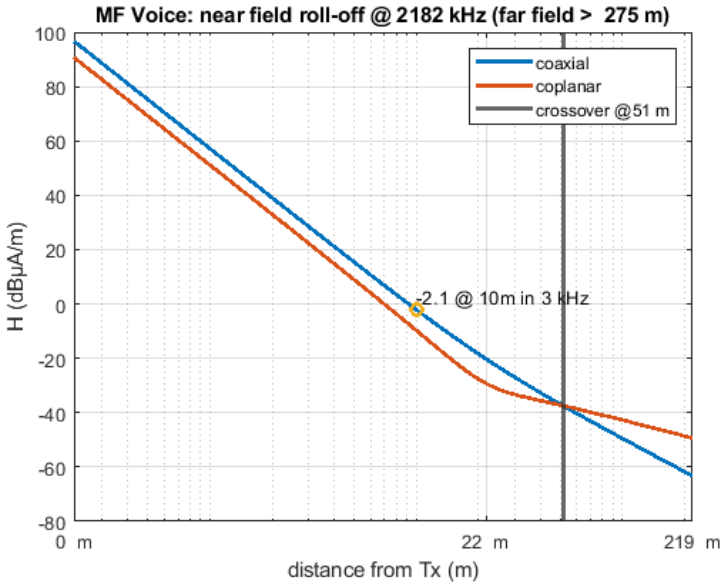


Figure 11: Roll-off function of H field at 2182 kHz

According to MSC.512 (105) [18] the MF Voice's sensitivity is given as E field of 6 µV/m. According to Recommendation ITU-R M.1467-1 [19] 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 [13], limited to 51.5 dB. It explains the dominant magnetic field for small distances. This conversion factor is plotted in Figure 12.

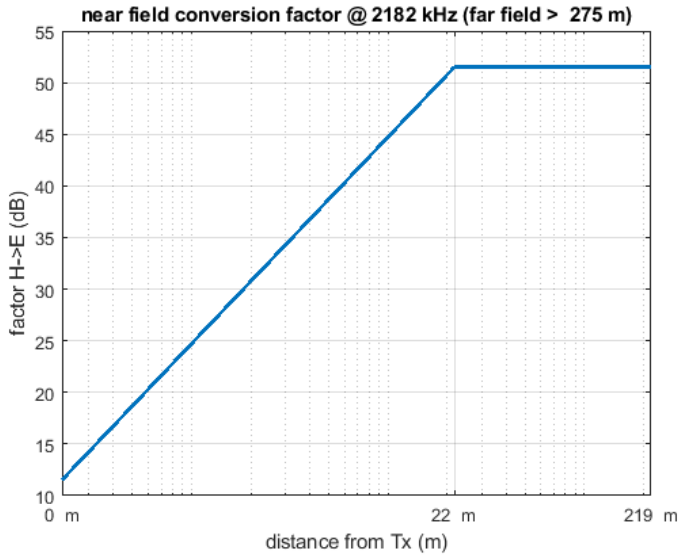


Figure 12: Near field conversion factor between H and E fields

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

Figure 12 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 [12]. 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.

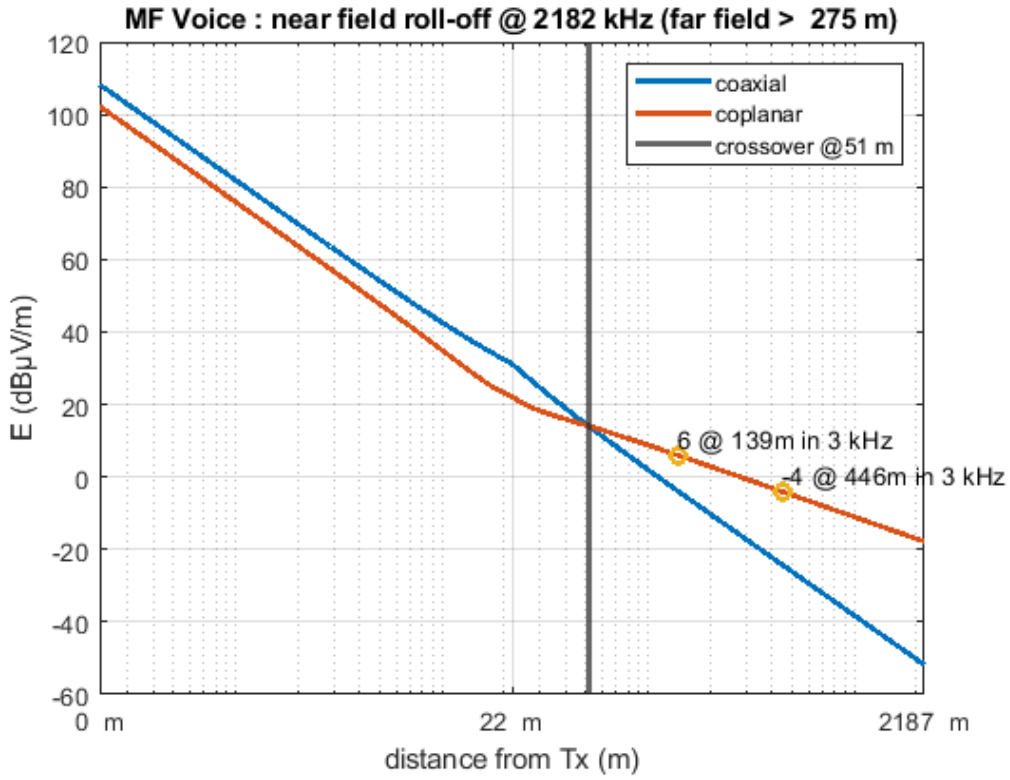


Figure 13: Roll-off function of H field at 500 kHz

4.1.1.6 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 14 and Figure 15 examples are given. The distance of 50 m is plotted there as well, which can be considered as a typical distance.



Figure 14: Distance from a company's car park to a ship lock in Hamburg (Source: Google Maps, 2025)



Figure 15: Distance from a public car park of a train station to a ship lock in Manchester

4.1.1.7 Summary and conclusions

Table 5 gives an overview of the results for each studied victim system based on the various interference criteria used in this report for these systems. 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 [13] are calculated.

Table 5: Study results

Victim system	Sep. distance (ERC Recommendation 74-01)	Sep. distance (ERC Recommendation 74-01 - 10 dB)	Sep. distance (ERC Recommendation 74-01 – 20 dB)	Sep. distance (ERC Recommendation 74-01 – 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
Note1: 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 [13] are between 22 m for DGNSS and 446 m for MF voice. They apply for maritime service receivers operating at their lowest possible level of reception.

Considering light electrical vehicles, examples of real world distances between car parks and ship locks can be around 50 m. According to the calculations done, 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 emissions would be needed.

4.1.2 Study B: Impact of "unwanted emissions of WPT devices" on the Maritime Service

In this study, 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 in accordance with values recommended in ERC Recommendation 74-01 [13]. These values presented in the unit dBuA/m are defined for emissions within a bandwidth of 10 kHz and a distance of 10 m 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, formulas 8, 6, 9 on page 7 [11]. 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. The model used is from electrodynamic and antenna theory [Balanis – Antenna theory: analysis and design] [34] as given 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 14 shows the magnetic field and electric field strengths calculated using the above- 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.

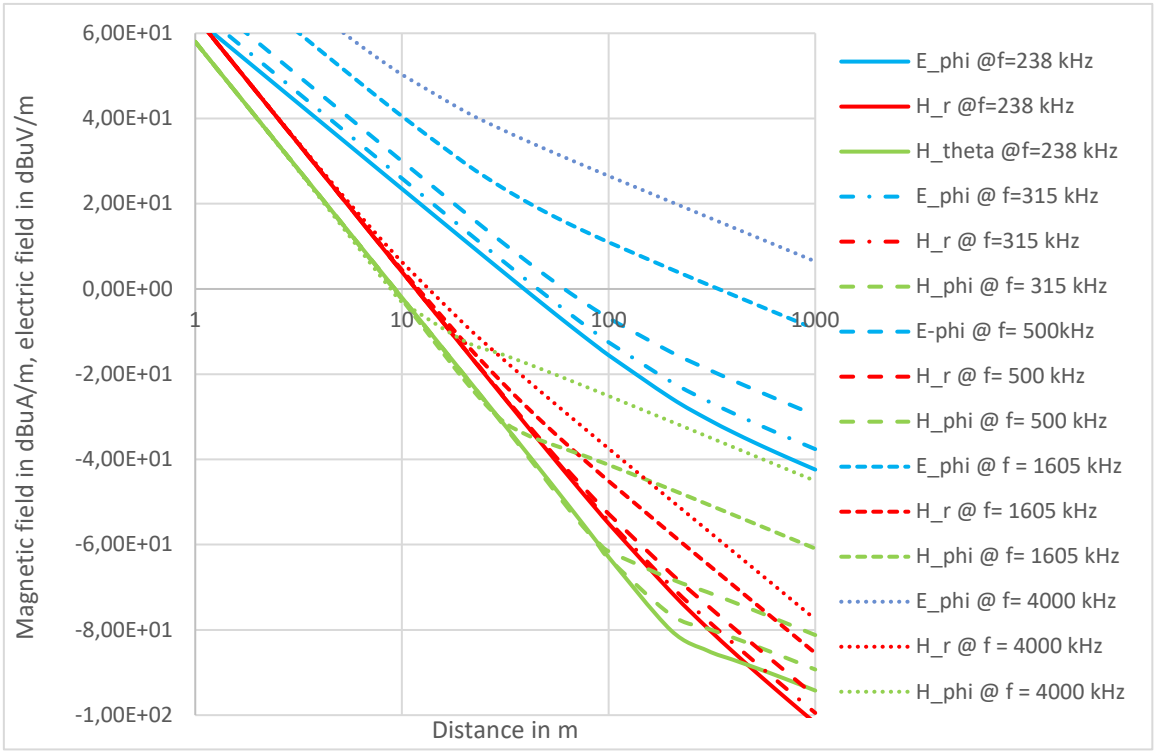


Figure 16: Field strength of an electrically small loop antenna carrying a magnetic moment of 1 nAm2

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.

The interference analysis in this study is based on the assumption of two different emission field strength values: -15 dBµA/m or -35 dBµA/m @ 10 m 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 [31] are considered in this study. 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 [32]. 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 6.

Table 6: 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 [31] are based on a SINAD = 20 dB for the modulation J3E. Accordingly, a bandwidth of 3 kHz is considered. With a protection criterion I/N = -6 dB, the interference signal level should not exceed the field strength of -9.7 dB – 20 dB – 6 dB = -35.7 dBµV/m @ f = 1605 kHz and -1.8 dB – 20 dB – 6 dB = -27.8 dBµV/m @ f = 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 [31]. It is assumed 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.372-16 [3]. The calculated field strength values are shown in Table 7. 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 7: Radio noise field strengths

Frequency range	Band-width	Radio noise magnetic field strength $H_{radionoise}$		Radio noise electric field strength $E_{radionoise}$	
		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 should be noted that the values given in Table 7 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 the worst case scenario.

However, Recommendation ITU-R M.2058 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 can be considered. This interference level may be interpreted as acceptable for this best-case scenario. Therefore, in this - 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 scenarios.

In best case scenarios those study parameters were selected which reduce the calculated level of interference to the possible minimum (e.g. receiver sensitivity). These scenarios represent the opposite case to worst case scenarios where study parameters are selected which increase the calculated level of interference to the possible maximum.

The receiver sensitivity values and corresponding protection criterions are summarised in Table 8. 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 8: Protection field strength levels

Frequency	Receiver Bandwidth	Sensitivity	E_{prot}	H_{prot}	Scenario type
1605 kHz	3 kHz	20 dBµV/m	-9 dBµV/m	-60.5 dBµA/m	(see Table 7)
4000 kHz	3 kHz	20 dBµV/m	-9 dBµV/m	-60.5 dBµA/m	(see Table 7)
1605 kHz	3 kHz	-9.7 dBµV/m	-16.6 dBµV/m	-68.1 dBµA/m	Worst case
4000 kHz	3 kHz	-1.8 dBµV/m	-19.7 dBµV/m	-71.2 dBµA/m	Worst case
1605 kHz	3 kHz	-9.7 dBµV/m	4.4 dBµV/m	-47.1 dBµA/m	Worst case
4000 kHz	3 kHz	-1.8 dBµV/m	2.3 dBµV/m	-49.2 dBµA/m	Worst case

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 the following Table 9.

Table 9: Separation distances

Receiver parameters			Separation distances			
Frequency	Bandwidth	Receiver Antenna	WPT emission limit	Table 7 assumption	Worst case	
					Quiet receiving site	Median City man made noise
1605	3 kHz	Magnetic Electric	-35	30.7 m 19.8 m	43.2 m 35.6 m	17.1 m 10.0 m
4000	3 kHz	Magnetic Electric	-35	67 m 67 m	238 m 238 m	22.9 m 21.8 m
1605	3 kHz	Magnetic Electric	-15	104 m 104 m	263 m 263 m	41.2 m 32.2 m
4000	3 kHz	Magnetic Electric	-15	664 m 664 m	848 m 848 m	187 m 187 m

4.2 BROADCASTING, AMATEUR, AERONAUTICAL RADIONAVIGATION, STFS, FIXED AND MOBILE SERVICES

For the Broadcasting, Amateur, Aeronautical Radionavigation, SFTS, Fixed and Mobile Services below 30 MHz, it is assumed that the considerations and conclusions in ECC Report 333 apply equally to unwanted emissions from higher power WPT applications.

Relevant sections of ECC Report 333 for these services are listed below:

4.2.1 Broadcasting

- ECC Report 333, executive summary
- ECC Report 333, annex 3: Detailed information on the protection of the Broadcasting Service from generic WPT;
- ECC Report 333, annex 4: Performance of an MF AM sound broadcasting receiver in the presence of interference from WPT;
- ECC Report 333, annex 9: Practical Coexistence measurements of WPT and AM receiver.

4.2.2 Amateur service

- ECC Report 333, annex 1: Studies into Impact of WPT Emissions on the Amateur Service
- In addition to the findings of ECC Report 333, material received while developing this addendum suggested that, taking into account additional mitigations, the same level of unwanted emissions from WPT as in Table 1 of ECC Report 333 for the Broadcasting Service, could also be sufficient to prevent interference to the Amateur Service.

4.2.3 Aeronautical Radionavigation

- ECC Report 333, annex 10: Impact Study of Non-Beam Inductive WPT Applications in 300–400 kHz on the Aeronautical Radionavigation Service

4.2.4 STFS

- ECC Report 333, section 3.7: Standard Frequency and Time Signal Service

4.2.5 Fixed and Mobile services

- ECC Report 333, section 4.8: Impact on the Fixed and Mobile Services Below 30 MHz (Minimum Coupling Loss)

4.3 RADIO ASTRONOMY SERVICE

4.3.1 Compatibility study between RAS and WPT operating below 30 MHz

4.3.1.1 Outline of the study

The analysis presented in this Addendum is limited to single-entry study and includes both adjacent scenario with some RAS bands and possible interference from WPT into RAS bands. The calculations in this study have been performed with the free open-source software package for Python, pycraf [24]. Previous analysis of radiated emission from generic SRD is reported in ECC Report 67 [6] and the issues on RFID emission on the adjacent band at 13 MHz are covered in ERC Report 074 [7].

4.3.1.2 RAS receiver parameters

Protection criteria for RAS are defined in Recommendation ITU-R RA.769-2 [20] and summarised in the below table.

Table 10: RAS technical parameters

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	
Electric field strength, E_{limit}	13.385 MHz: -54.9 dBµV/m	Derived from Recommendation ITU-R RA.769-2 Table 1 for continuum observation. Assumption of free space propagation ($E_{rms} = \sqrt{PFD \cdot Z_0}$, $Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 376.73\ \Omega$) (see Report ITU-R RA.2131-0 [35].
	25.610 MHz: -52.5 dBµV/m	

4.3.1.3 Details of the study

This analysis considers several standards, including ETSI and CISPR, to assess the spurious emission characteristics of WPT.

According to ETSI EN 303 417 [22], which deals specifically with wireless power transmission systems the radiated emission values are given in Table 11. WPT systems (up to 31.5 W) operate in the band 13.553-13.567 MHz, which is close to the 13.36-13.41 MHz RAS primary band. Despite the proximity of these bands, the analysis is conducted as a spurious emission according to Figure 4 of ETSI EN 303 417. Figure 15 shows the scheme of OOB and spurious domain of WPT system [32]. Therefore, the radiated emissions expressed as magnetic field strength are considered with spurious emissions of -3.5 dBµA/m and -25 dBµA/m respectively for operating and standby mode.

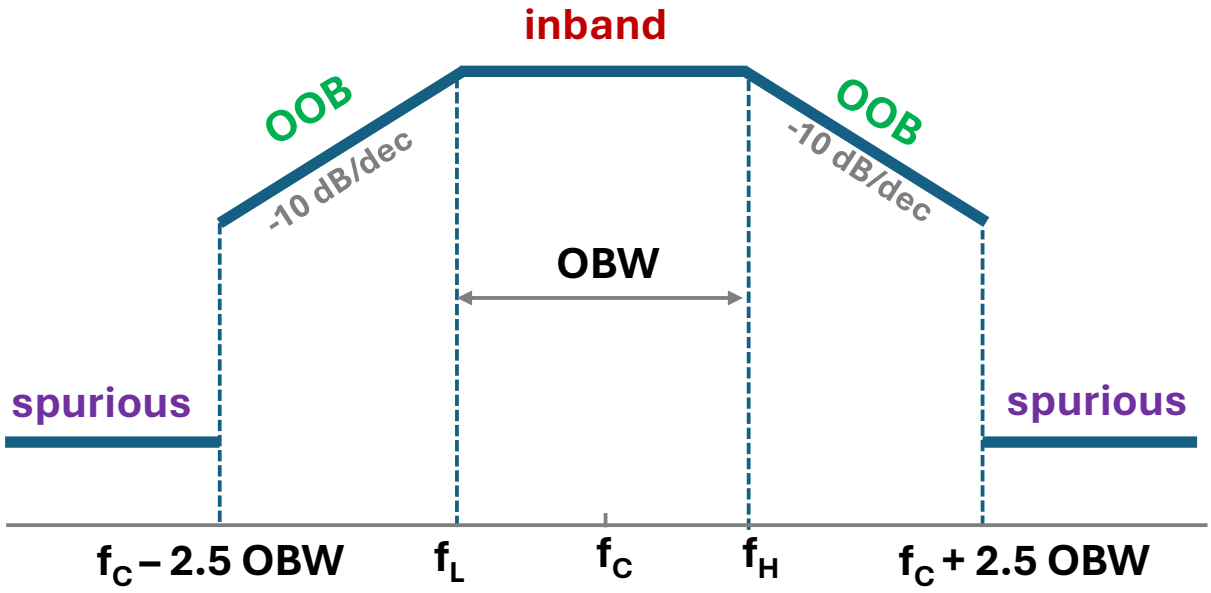


Figure 17: Out of band and spurious domain of WPT system

Table 11: Radiated Magnetic field strength of spurious emissions below 30 MHz according to ETSI EN 303 417, table 4

State	Frequency 9 kHz ≤ f < 10 MHz	Frequency 10 MHz ≤ f < 30 MHz
Operating	27 dBµA/m at 9 kHz descending 10 dB/dec	-3.5 dBµA/m
Standby	5.5 dBµA/m at 9 kHz descending 10 dB/dec	-25 dBµA/m
NOTE: "Operating" means mode 2, 3 and 4 "Standby" means mode 1 according to ETSI EN 303 417, table 2		

In ECC Report 333, which covers low power WPT, the assumption of spurious emission levels is reported in table 41 . The values of spurious emissions are shown in Table 12, however it is not clear if these values are suitable also for higher power WPT.

Table 12: WPT spurious emissions according to ECC Report 333, table 41

Scenario	Value
WPT max. emissions (worst alignment)	-15 dBµA/m at 10 m
WPT min. emissions (best alignment)	-30 dBµA/m at 10 m

The emission limits according to CISPR 11 [23], and CISPR 14-1 [24], (see ETSI EN 303 417, table 6).) are shown in Figure 16 and Table 13. The distance range specified in CISPR 11 for conducting in-situ measurements is between 30 m and 100 m (see ETSI EN 303 417, figure 3 [22]). The minimum distance value of 30 m has been assumed in the calculations.

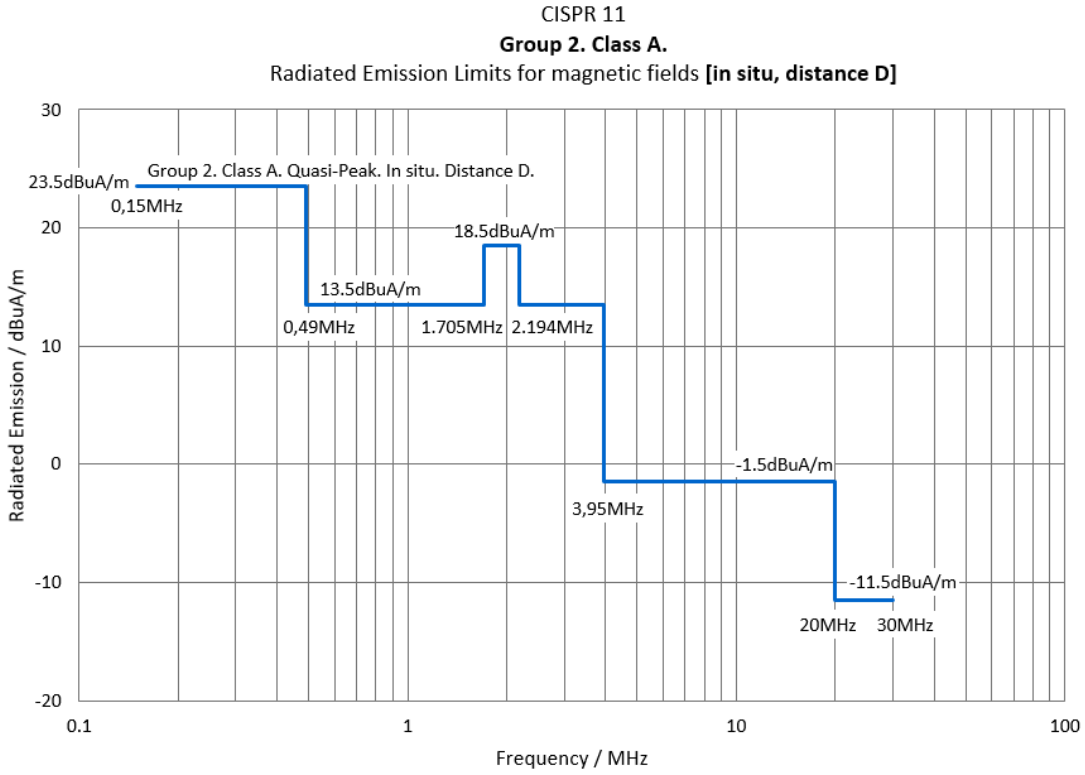


Figure 18: Emission limits for industrial, scientific, and medical electrical equipment (ISM) (according to CISPR 11 Group 2 Class A [23])

Table 13: Emission limits for induction cooking appliances and similar apparatus according to CISPR 14-1 [29]

Frequency range (MHz)	Limits at 3 m distance Quasi-peak (dBµA/m)
0.009-0.070	69
0.070-0.150	69 Decreasing linearly with logarithm of frequency to 39
0.150-4.0	39 Decreasing linearly with logarithm of frequency to 3
4.0-30	3
NOTE 1 The limits of this table apply to induction cooking appliances intended for commercial use and those for domestic use with a diagonal diameter of more than 1.6 m NOTE 2 The measurements are performed at 3 m distance with a 0.6 m loop antenna as described in 4.2.1 of CISPR 16-1-4 NOTE 3 The antenna shall be vertically installed, with the lower edge of e loop at 1 m height above the floor.	

The propagation model used is Recommendation ITU-R SM.2028-0 [25] and the methodology used is also described in ERC Report 69 [11] and it is based on data from Rec. ITU-R P.0 [26]368, which provides guidance on the conduct of compatibility studies (for further details, see ITU handbook on Ground Wave Propagation [39]).[27]). This model is suitable for modelling propagation attenuation for signals from 10 kHz up to 30 MHz. A similar approach is taken in WPT compatibility studies in Report ITU-R SM.2449-1. Note that ITU-R P.452 [28] is not valid, however similar results can be inferred by considering the lowest suitable frequency of 100 MHz. Ground wave propagation has been considered as RAS sites are ground based with typical land characteristics ($\sigma = 3\ mS/m,\ \varepsilon_r = 22$) [27] and the victim threshold limits are derived from ITU-R RA.769-2 [20] (see Table 4). Moreover, all calculations are made in the far field, which is reasonable given the frequency bands of interest. For simplicity, the centre frequencies of RAS bands equal to 13.385 MHz and 25.610 MHz are used as references in the calculation.

The procedure to determine the separation distance is shown .below. Firstly, the magnetic dipoles (coaxial, coplanar) m_1, m_2 are computed, as described in [11], [29]. Then, by selecting the maximum of the two (typically the coaxial case), the effective radiated power (ERP) is computed as follows:

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

Where λ_r is the radian wavelength, also known as wavenumber ($\lambda/2\pi$). The Electric field strength limits (E_{limit}) are derived from ITU-R RA.769 [20]. The acceptable interference level (E_{int}) is computed using the following formula, as ITU-R SM.2028-0 [26] (to Recommendation based on ITU-R P.368 [25] data) provides the table $E_{asyntote,40}$ $(dB\mu V/m)$ to convert the reference emission of 1 kW at a distance of 1 km to the actual emission (refer to [36] [16] for details). Note that ERP need to be converted into dBkW.

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

Based on the assumptions, the signal the is subjected to an attenuation of 40 dB/decade. The separation distance (based on ground wave propagation) between the WPT transmitter and the RAS station is calculated as:

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

Table 14: Separation distances according to ETSI EN 303 417 [22] spurious emission

RAS band (MHz)	Radiated emission, Hm	ERP	Separation Distance according to ITU-R SM.2028-0 (ground wave propagation)
13.36-13.41	Operating mode: -3.5 dBµA/m at 10 m	-96.1 dBkW	14.0 km
	Standby mode: -25 dBµA/m at 10 m	-117.6 dBkW	4.1 km
25.55-25.67	Operating mode: -3.5 dBµA/m at 10 m	-90.1 dBkW	11.5 km
	Standby mode: -25 dBµA/m at 10 m	-111.6 dBkW	3.3 km

Table 15: Separation distances according to ECC Report 333 (low power WTP), table 41 spurious emission

RAS band (MHz)	Radiated emission, Hm	ERP	Separation Distance according to ITU-R SM.2028-0 (ground wave propagation)
13.36-13.41	Max WPT emission (worst alignment): -15 dBµA/m at 10 m	-107.6 dBkW	7.2 km
	Min WPT emission (best alignment): -30 dBµA/m at 10 m	-122.6 dBkW	3.0 km
25.55-25.67	Max WPT emission (worst alignment): -15 dBµA/m at 10 m	-101.6 dBkW	5.9 km
	Min WPT emission (best alignment): -30 dBµA/m at 10 m	-116.6 dBkW	2.5 km

Table 16: Separation distances according to CISPR 11 [23] and CISPR 14-1 [24]

RAS band (MHz)	Reference	Radiated emission, Hm	ERP	Separation Distance according to ITU-R SM.2028-0 (ground wave propagation)
13.36-13.41	CISPR 11 (Group 2, Class A)	-1.5 dBµA/m at 30 m	-74.5 dBkW	48.2 km
25.55-25.67		-11.5 dBµA/m at 30 m	-78.9 dBkW	22.0 km
13.36-13.41	CISPR 14-1	3 dBµA/m at 3 m	-104.5 dBkW	8.6 km
25.55-25.67			-101.3 dBkW	6.0 km

4.3.1.4 Consideration of harmonics

WPT can generate harmonics, potentially causing interference in RAS allocated bands. While bands below 30 MHz are used by several radiocommunication services, many sensitive RAS observations remain feasible.

Harmonics generated by WPT systems may affect bands above 30 MHz. Therefore, the calculated separation distances, considering spurious emissions, are relevant for RAS frequency bands above 30 MHz.

4.3.2 Compatibility study between RAS and WPT spurious and harmonics emissions above 30 MHz

4.3.2.1 Outline of the study

This study examines the spurious and harmonic emissions stemming from WPT systems, assumed to be as shown in Table 17, (ETSI EN 303 417, table 5 [22]) which partially reflect the values reported in Recommendation ITU-R SM.329-12, table 3 [29] (Short range devices operating below 30 MHz). In this study, harmonic emissions are considered part of spurious emissions; therefore, both harmonics and spurious emissions are treated in the same manner. Furthermore, the radiated spurious emission levels are considered as absolute power, as the reference bandwidth to which *e.i.r.p.* refers is not explicitly stated in the reference documents.

Table 17: Radiated spurious emission of WPT between 30 MHz and 1 GHz

State (see note)	47 MHz to 74 MHz 87.5 MHz to 118 MHz 174 MHz to 230 MHz 470 MHz to 790 MHz	Other frequencies between 30 MHz to 1000 MHz
Operating	4 nW	250 nW
Standby	2 nW	2 nW
NOTE: "Operating" means mode 2, 3 and 4 according to Table 2; "standby" means mode 1 according to ETSI EN 303 417 V1.1.1, table 2 [22]		

Given the sparse distribution of their application, a single-entry worst-case study was carried out. The calculations were conducted using the Python package pycraf [31].

4.3.2.2 Use of the band by RAS and regulatory status above 30 MHz

Above 30 MHz, RAS has five allocations, three with primary status and two with secondary status. The band 606-614 MHz is protected by footnote 5.149 of ITU Radio Regulations [8] which administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. The RAS bands considered in this study are sourced from the ECA table [4], which comprehensively catalogues all frequencies and applications used in Europe. The analysis focuses on the frequency range up to 1 GHz, as indicated in ERC Recommendation 74-01, table 1 [13].

Table 18: RAS frequency and allocation usage from 30 MHz to 1 GHz

RAS frequency bands	Allocation status	Type of RAS Observation
37.5-38.25 MHz	Secondary	Continuum
70.45-74.8 MHz	Secondary	Continuum
150.05-153 MHz	Primary	Continuum
322-328.6 MHz	Primary	Continuum, spectral line and VLBI
406.1-410 MHz	Primary	Continuum, VLBI
606-614 MHz	5.149	Continuum, VLBI

4.3.2.3 Details of the study

As the propagation model outlined in Recommendation ITU-R P.452-17 [28], typically employed for compatibility assessments, is considering 100 MHz and above, this study focuses exclusively on radio spectrum frequencies above 100 MHz.

The performed analysis is restricted to generic site with flat earth assumption. Furthermore, no clutter was considered as the analysis is limited to single-entry worst-case scenario. The below tables show the technical parameters of respectively WTP and RAS.

The protection criteria for RAS are outlined in Recommendation ITU-R RA.769, table 1 for continuum observations [20], which are based on an integration time of 2000 seconds.

Table 19: WPT technical parameters

System Parameter	Value	Remarks
Antenna generic WPT height, h_{WPT}	1.5 m	
WPT spurious emission (operating mode), P_{TX}	151.525 MHz: -36 dBm	According to ETSI EN 303 417 V1.1.1 [22]
	325.3 MHz: -36 dBm	
	408.05 MHz: -36 dBm	
	611 MHz: -54 dBm	

Table 20: Radio astronomy technical parameters

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
Antenna RAS height, h_{RAS}	30 m	
Threshold interference power flux density level, PFD_{limit}	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 calculated separations distances are reported in the below table. Since almost all RAS stations observe above 30 MHz, these separation distances should be applicable to all RAS stations.

The result of this study shows particularly large exclusion zones, ranging from a few kilometres to several tens of kilometres. Furthermore, although such devices operate at frequencies below 30 MHz, they may also have impact on frequencies above 30 MHz.

Table 21: Calculated Separation distances based on maximum spurious emission limits from ETSI EN 303 417 [22] for generic high power WTP

RAS band	WPT state	Spurious emission	Separation Distance according to ITU-R P.452 [38]
150.05-153 MHz	Operating mode	250 nW (-36 dBm)	28.2 km
	Standby mode	2 nW (-57 dBm)	4.8 km
322-328.6 MHz	Operating mode	250 nW (-36 dBm)	18.5 km
	Standby mode	2 nW (-57 dBm)	5.2 km
406.1-410 MHz	Operating mode	250 nW (-36 dBm)	20.2 km
	Standby mode	2 nW (-57 dBm)	5.9 km
606-614 MHz	Operating mode	4 nW (-54 dBm)	6.8 km
	Standby mode	2nW (-57 dBm)	5.6 km

4.3.3 Site specific study of LOFAR Core station

The impact of WPT on RAS was 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 V1.1.1. The primary RAS allocated band of 150.05-153 MHz is within the operational range of LOFAR. The propagation model used is ITU-R P.452 with a time percentage of 2%. The protection criteria are based on ITU-R RA.769, which defines a power threshold of -199 dBW (continuum observations), and it is assumed a RAS antenna height of 1 m. The LOFAR core station (see Table 8) is chosen as the example site, with Lidar Terrain Data [26]Fare clic o toccare qui per immettere il testo.. Figure 17 illustrates the calculated separation distance to protect the RAS station from WPT interference in an outdoor scenario.

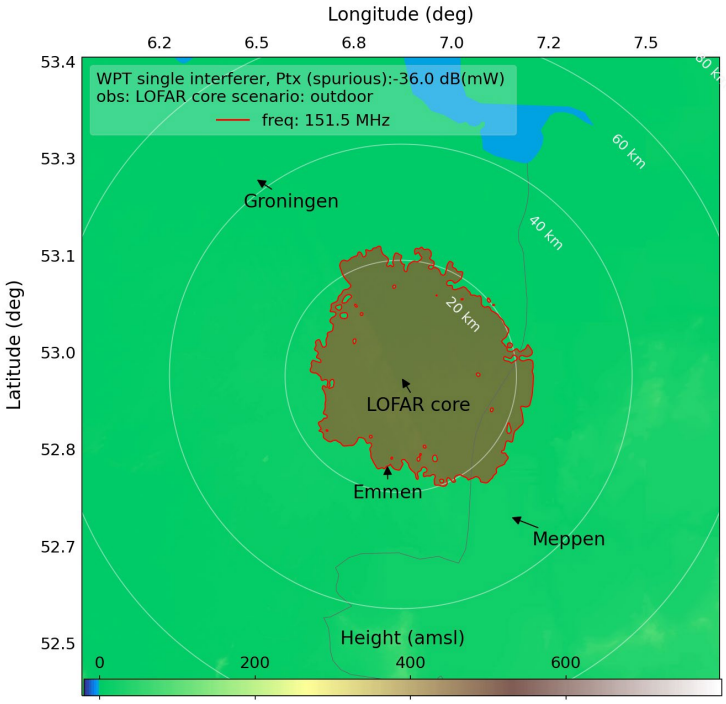


Figure 19: Calculated separation distance of LOFAR core station at 151.5 MHz, scenario: outdoor

The resulting separation distance is 20 km, which in accordance with the results of the previous study below 30 MHz in which 14 km was derived, despite the different conditions (mainly in terms of emission and propagation) that apply in that frequency range.

4.3.4 Conclusions

This study examined generic higher-power WPT applications, operating in the frequency band 13.553-13.567 MHz, which is in close proximity to the RAS primary band at 13.36-13.41 MHz. The analysis was conducted based on the spurious emission which is therefore applicable to all WPT systems. The results indicate a range of separation distances corresponding to specific radiated emission. These are associated with different operational states. For WPT systems in standby mode, the separation distance ranges from 3.3 km to 4.1 km, while for systems in operating mode, it extends from 11.5 to 14 km. Conversely, according to CISPR 11 [34], the separation distance is 22.0 km to up to 48.2 km, with a radiated emissions of -1.5 dBµA/m at 30 m. While the separation distance according to CISPR 14-1 [35] ranges from 6.0 km and 8.6 km depending on the frequency. Additionally, a specific study of spurious emissions above 30 MHz up to 1 GHz suggests that the required separation distance should be 28.2 km and a site-specific study of the LOFAR core station at 155 MHz indicates a separation distance of around 20 km. To be consistent with other studies of different services presented in this Addendum Report, most of which agree that a limit of -35 dBµA/m at 10 m is appropriate to minimize the risk of interference, a minimum separation distance of 2.3 km would be required for RAS. Conversely, if the limit is set at -20 dBµA/m, a minimum separation distance of 5.4 km would be necessary.

4.4 CORDLESS KITCHEN WPT

4.4.1 Emission simulations and measurements

4.4.1.1 Inductive power sources



Figure 20: Inductive power sources

4.4.1.2 Variance of kitchen use cases

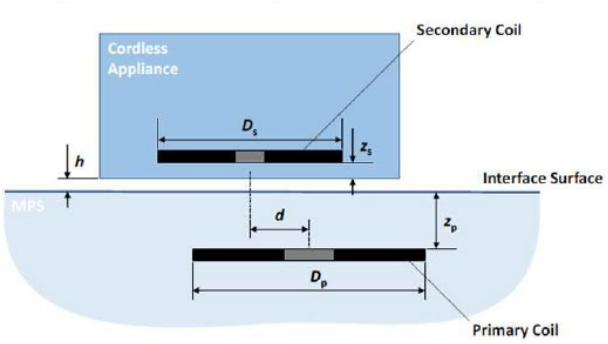


Figure 21: Mechanical model of a kitchen use case

The following parameters establish the mechanical model which can be seen in Figure 19:

- D_p is the outer diameter of the Primary Coil;
- z_p is the distance from the Primary Coil to the Interface Surface;
- D_s is the outer diameter of the Secondary Coil;
- z_s is the distance from the Secondary Coil the Interface Surface;
- d is the alignment tolerance between the axes of the Primary Coil and the Secondary Coil;
- h is the height of the Cordless Appliance above the Interface Surface.

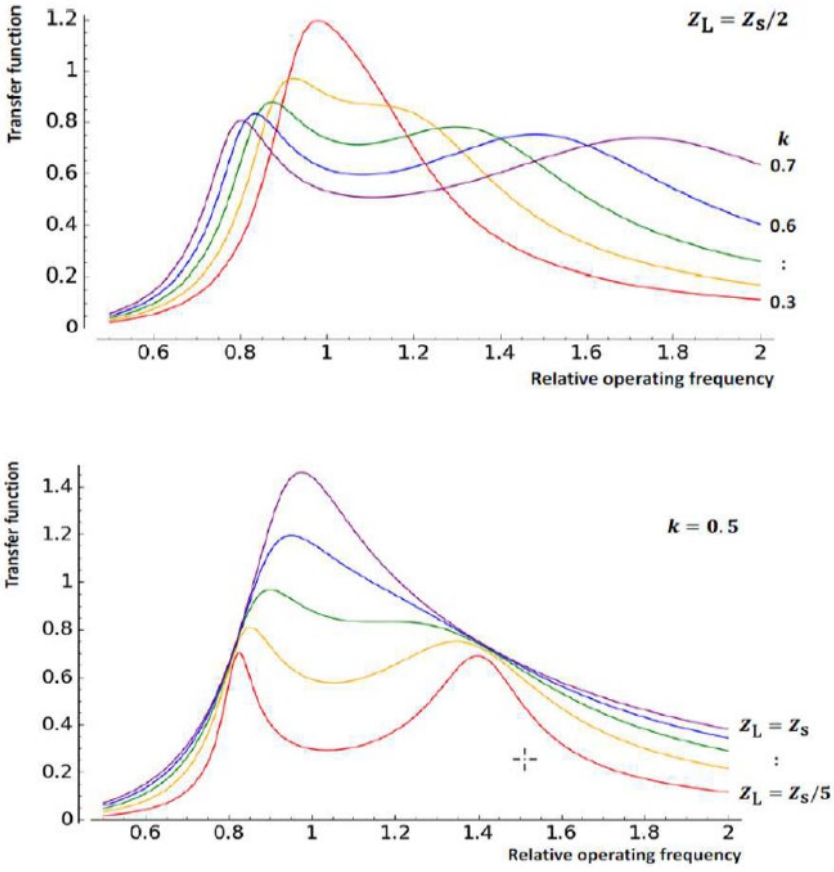


Figure 22: Transfer function for variance of a kitchen use case

Furthermore the standard allows a coil-to-coil distance variation of 8 to 40 mm, and a receiver coil diameter of 80 to 210 mm. The received load power is in the range of 0 to 2200 W.

4.4.1.3 Cordless Kitchen Emission Simulations

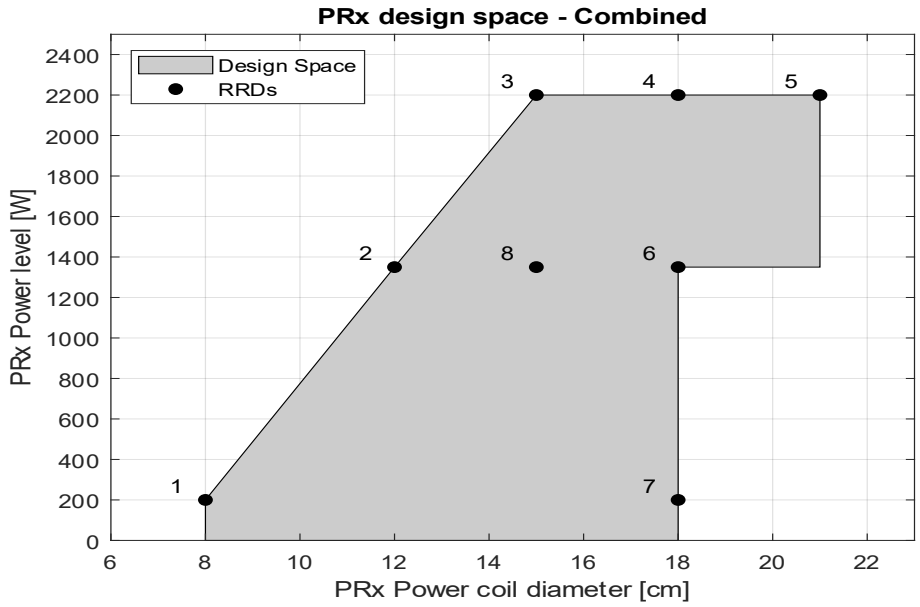


Figure 23: Receiver variation

Table 22: Power and size range of cordless kitchen appliances

Receiver side					Transmitter side					
System Design Parameters					Cooktop case (Lp = 56u, z=1.2 cm)			Countertop case (Lp = 60u, z=4 cm)		
fs = 30.0 KHz / Qs = 50					fp = 26.8 kHz / Qp = 30 / D = 180 mm			fp = 30.0 kHz / Qp = 33 / D = 210 mm		
			Uload = 115V	Uload = 230V						
RRD#	Power [W]	Dcoil [cm]	Ls nom [uH]	Ls nom [uH]	K	f_op [kHz]	I_p [A rms]	K	f_op [kHz]	I_p [A rms]
1	200	8.0	527	2106	0.36	48.0	11.0	0.16	37.6	21.1
2	1350	12.0	120	481	0.60	48.2	19.4	0.26	35.7	30.9
3	2200	15.0	70	280	0.70	24.0	25.1	0.34	35.2	29.7
4	2200	18.0	55	221	0.75	24.0	23.7	0.39	34.4	26.9
5	2200	21.0	53	210	0.74	24.2	23.8	0.43	33.2	24.8
6	1350	18.0	80	321	0.75	27.2	14.5	0.39	37.9	22.6
7	200	18.0	83	333	0.75	68.0	5.6	0.39	39.1	17.1
8	1350	15.0	92	368	0.70	53.4	16.4	0.34	37.2	25.0

Coupling factor and operating variance => K=0,16-0,75 f_op = 20-74 kHz

4.4.1.4 *Spice simulation model*

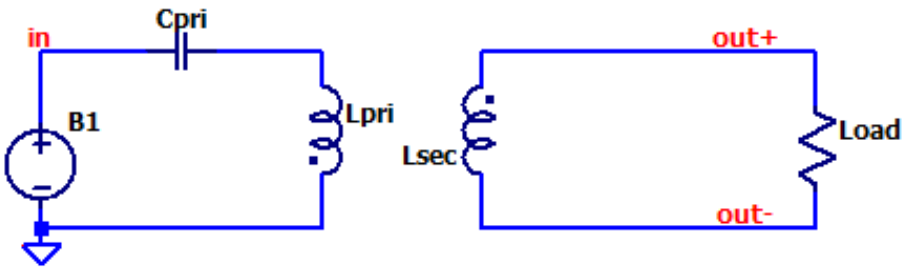


Figure 24: Induction hob with linear load (pan)

Simulated components:

- Voltage source: Often a half-bridge;
- Load: With only a resistor, the system behaves mostly linear.

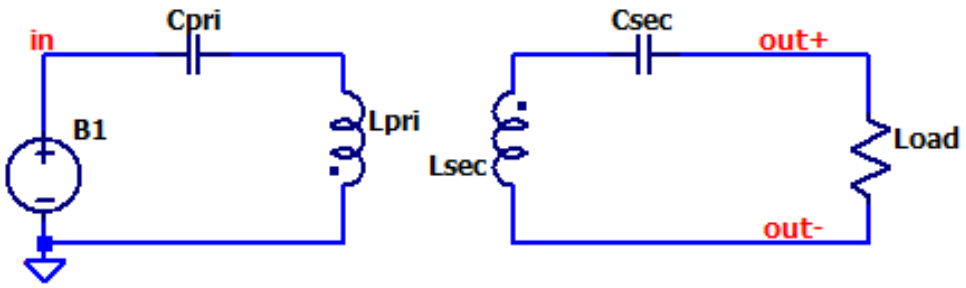


Figure 25: Transmitter with non-linear receiver

Simulated components:

- Voltage source: Often a half-bridge which as a 100 Hz (or 120 Hz) amplitude modulation and has zero crossing gap;
- Resonant circuit: Contains power coils and resonant capacitors: Coupling factor based on measurements for cooktop and countertop case and reference receiver #3;
- Load: With only a resistor, the system behaves linear.

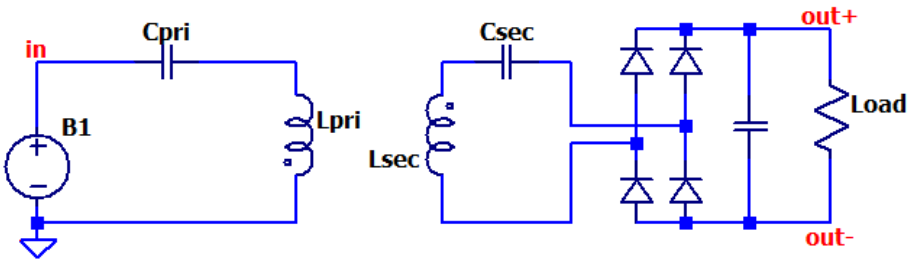


Figure 26: Transmitter with linear receiver

Simulated components:

- Voltage source: Often a half-bridge which as a 100 Hz (or 120 Hz) amplitude modulation and has zero crossing gap;
- Resonant circuit: Contains power coils and resonant capacitors: Coupling factor based on measurements for cooktop and countertop case and reference receiver #3;
- Load: With only a resistor, the system behaves linear. With a rectifier and capacitor the system behaves non-linear.

4.4.1.5 System measurements

Countertop case (z=4 cm) with reference receiver #3



Figure 27: Measured currents and voltages on wireless power system countertop case (Transmitter: Yellow: U_converter, Blue: I_transmitter; Receiver: Green: U_receiver, Purple: I_receiver, Red: Secondary power U x I)

Measurements of countertop case in Figure 27 are obtained using following system parameters:

- Transmitter: f_p = 30 kHz;
- Receiver: f_s = 30 kHz;
- P= 1.9.kW => f_op =36 kHz;
- Harmonics of current related to sum of all harmonics: I_3 = 3%, I_5 = 1%.

4.4.1.6 Spice simulation for countertop case (z=4cm) with reference receiver #3

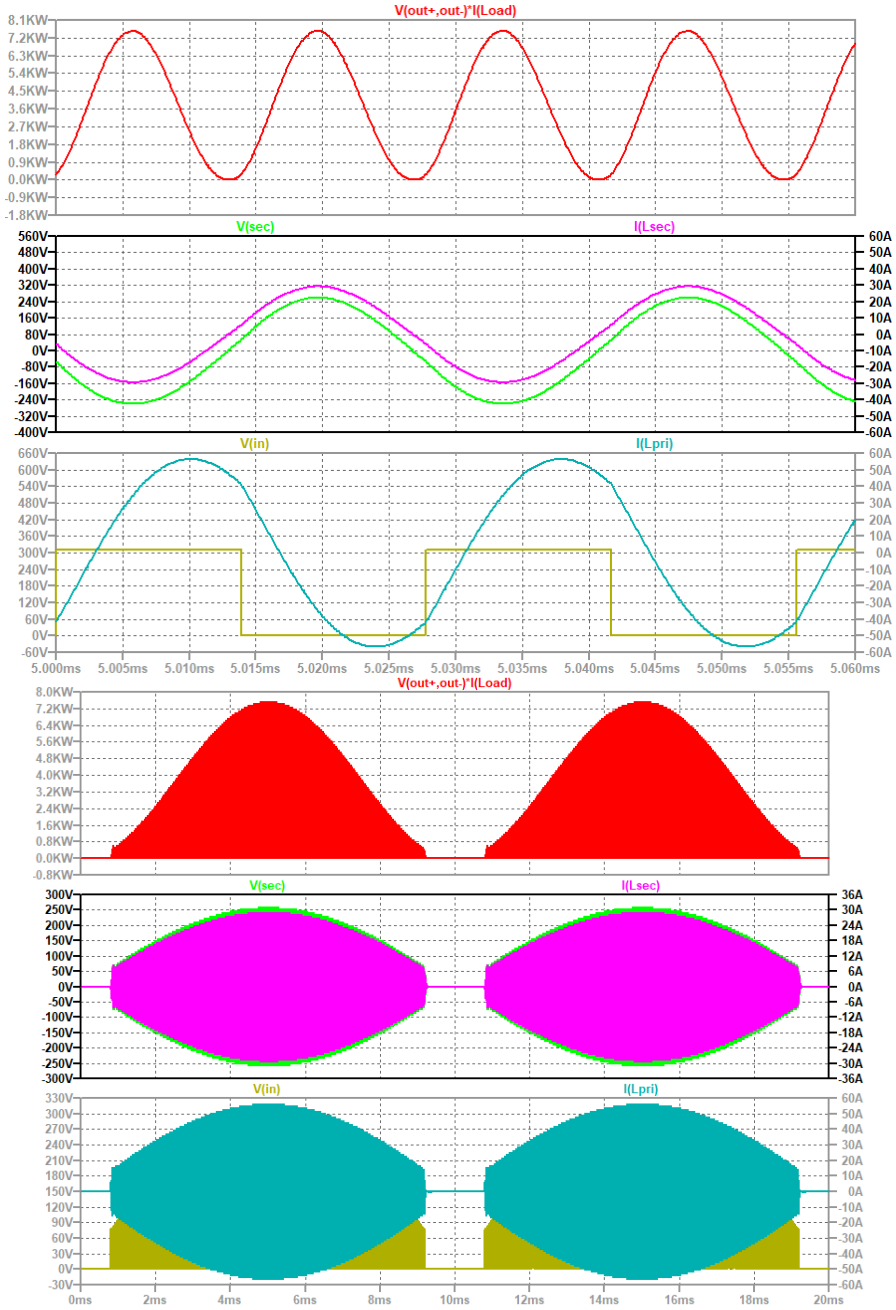


Figure 28: Simulated currents and voltages in wireless power system countertop case

Spice simulation for countertop case in Figure 28 is performed using following system parameters:

- L_primary: 56 uH;
- F_primary: 30 kHz;
- L_secondary: 100 uH;
- F_secondary: 30 kHz;
- Load: 8.8 Ohm;
- Coupling: 0,34;
- F_operate: 36 kHz.

Spice simulation is Figure 28 driven by half bridge with output power 1.85 kW, and results are identical with the measurements.

The harmonic components, DC components and total harmonic distortion of the half-bridge voltage and primary current are shown in the table below. The half-bridge voltage follows the square wave harmonics, which are mostly the odd harmonics when the square wave has a duty cycle of 50%. Filtered by the resonant circuit the harmonics of the primary current are reduced. I_3=3.71% (with respect to amplitude of main harmonic) and I_5=1.25%. The measurements and simulations produce the same results.

Table 23: Amplitude of the harmonics resonant system in the cooktop case

Harmonic Number	Normalised component of half-bridge voltage	Normalised component of primary current
1	1.000e+00	1.000e+00
2	2.667e-04	5.227e-05
3	3.334e-01	3.708e-02
4	2.534e-04	2.050e-05
5	2.001e-01	1.253e-02
6	2.314e-04	1.220e-05
7	1.430e-01	6.297e-03
8	2.030e-04	7.884e-06
9	1.112e-01	3.790e-03
10	1.704e-04	5.270e-06
11	9.101e-02	2.531e-03
12	1.370e-04	3.549e-06
13	7.700e-02	1.810e-03
14	1.077e-04	2.354e-06
15	6.672e-02	1.357e-03
16	8.894e-05	1.707e-06
17	5.885e-02	1.055e-03
18	8.637e-05	1.515e-06
19	5.264e-02	8.426e-04
20	9.678e-05	1.532e-06
DC component	95.8969 V	5.3939e-06 A
Total harmonic distortion	45.705%	3.999%

4.4.1.7 Cooktop case (z=1.2 cm) with reference receiver #3

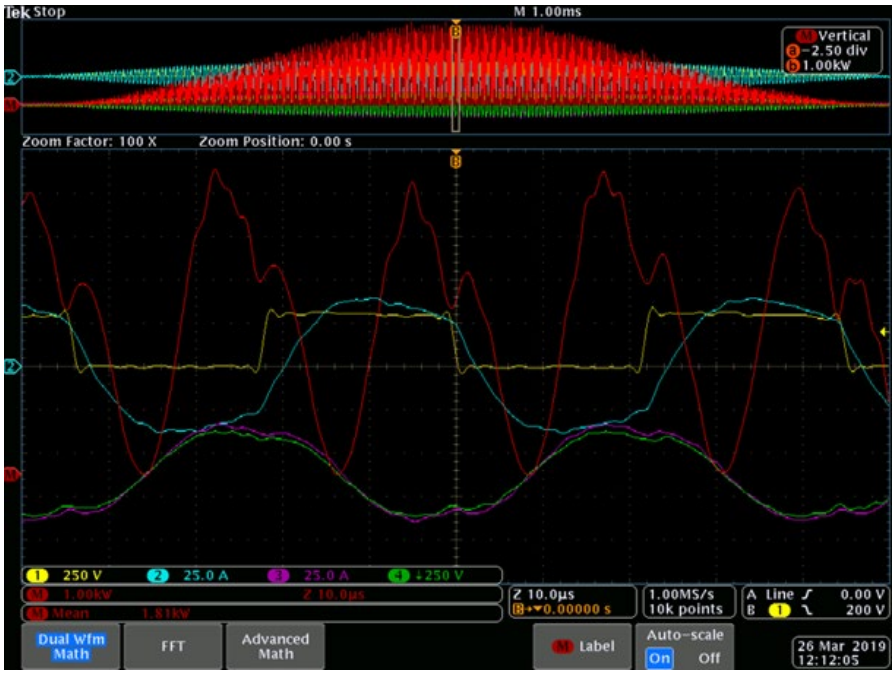


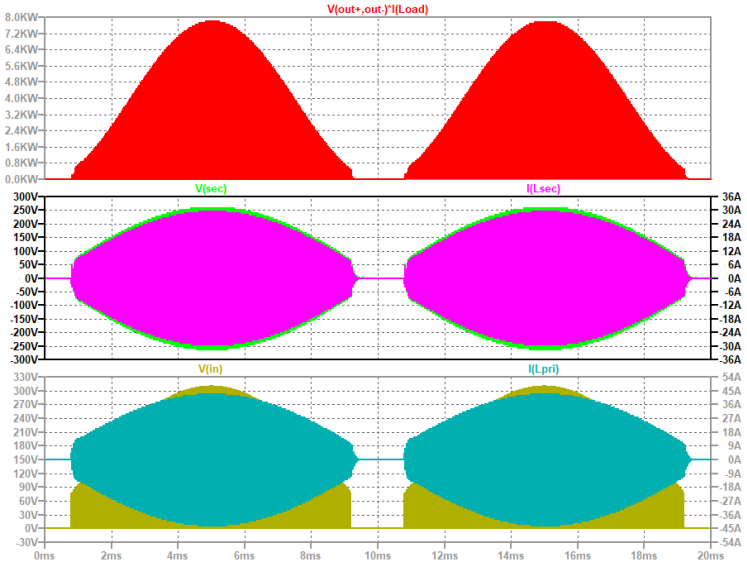
Figure 29: Measured currents and voltages on wireless power system cooktop case

Measurements of cooktop case in Figure 29 are obtained using following system parameters:

- Transmitter: f_p = 27 kHz;
- Receiver: f_s = 30 kHz;
- P= 1.8 kW => f_op =23 kHz;
- Harmonics of current related to sum of all harmonics: I_3 = 3%, I_5 = 3%;

Significant share of higher harmonics due to sub resonant operation point. Up to 30% for 3rd harmonic around 1 kW was measured.

Spice simulation for cooktop case (z=4 cm) with reference receiver #3



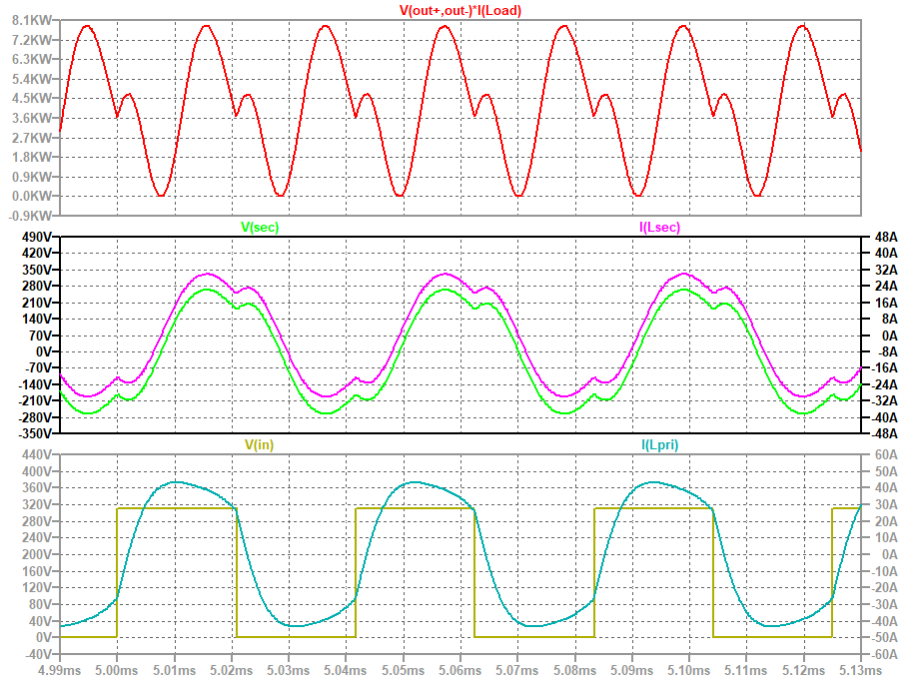


Figure 30: Simulated currents and voltages in wireless power system cooktop case

Spice simulation for cooktop case in Figure 30 is performed using following system parameters:

- L_primary: 56 uH;
- F_primary: 27 kHz;
- L_secondary: 100 uH;
- F_secondary: 30 kHz;
- Load: 8,8 Ohm;
- Coupling: 0.70;
- F_operate: 24 kHz.

Spice simulation is driven by half bridge, output power 2 kW, results are identical with the measurements.

The harmonic components, DC components and total harmonic distortion of the half-bridge voltage and primary current are shown in the table below. The half-bridge voltage follows the square wave harmonics, which are mostly the odd harmonics when the square wave has a duty cycle of 50%. Filtered by the resonant circuit the harmonics of the primary current are reduced. I_3=16.0% (with respect to amplitude of main harmonic) and I_5=4.43%. Results are identical with the measurements.

Table 24: Harmonic components, DC components and total harmonic distortion

Harmonic Number	Normalised component of half-bridge voltage	Normalised component of primary current
1	1.000e+00	1.000e+00
2	8.245e-04	5.680e-04
3	3.337e-01	1.579e-01
4	2.086e-04	6.256e-05
5	1.999e-01	4.425e-02
6	2.181e-04	3.824e-05
7	1.430e-01	2.087e-02

Harmonic Number	Normalised component of half-bridge voltage	Normalised component of primary current
8	2.020e-04	2.515e-05
9	1.111e-01	1.221e-02
10	5.785e-05	6.322e-06
11	9.089e-02	8.157e-03
12	1.734e-04	1.326e-05
13	7.701e-02	5.725e-03
14	6.082e-05	3.889e-06
15	6.663e-02	4.293e-03
16	1.193e-04	7.039e-06
17	5.887e-02	3.355e-03
18	1.122e-04	6.089e-06
19	5.265e-02	2.644e-03
20	5.836e-05	2.892e-06
DC component	95.8946 V	-9.8077e-06 A
Total harmonic distortion	45.711%	16.788%

4.4.1.8 Harmonics generation and attenuation

Harmonics caused by duty cycle control of a half bridge inverter:

$$a_0 = \int_{-1}^{1} f(t)\,dt = \int_{-D}^{D} V_+\,dt = 2 \times V_+ \times D$$

$$a_1 = 2 \times \frac{V_+}{\pi} \times \sin(\pi D)$$

$$a_2 = \frac{V_+}{\pi} \times \sin(2\pi D)$$

$$a_3 = \frac{2}{3} \times \frac{V_+}{\pi} \times \sin(3\pi D)$$

$$a_4 = \frac{1}{2} \times \frac{V_+}{\pi} \times \sin(4\pi D)$$

$$a_5 = \frac{2}{5} \times \frac{V_+}{\pi} \times \sin(5\pi D)$$

DC level and amplitude of the first five harmonics with a Pulse-width modulation (PWM) signal with certain duty cycle.

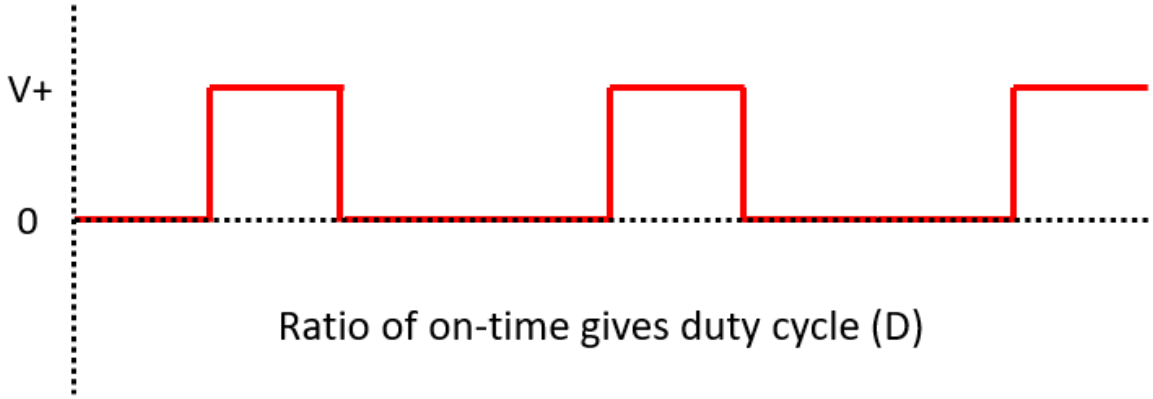


Figure 31: Example of a square wave voltage as generated by a half bridge inverter

DC level and amplitude of the first five harmonics with a PWM signal with certain duty cycle

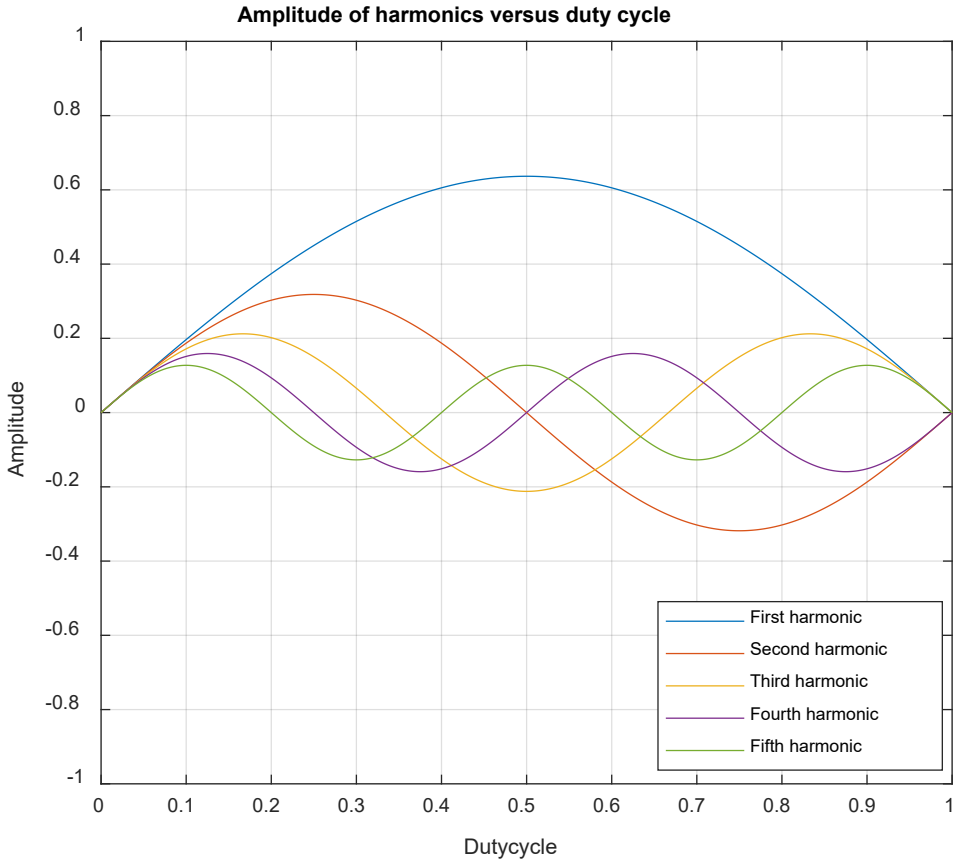


Figure 32: Amplitude of the harmonics of a square wave with varying duty cycle

Attenuation of the harmonics by the resonant system in the countertop case

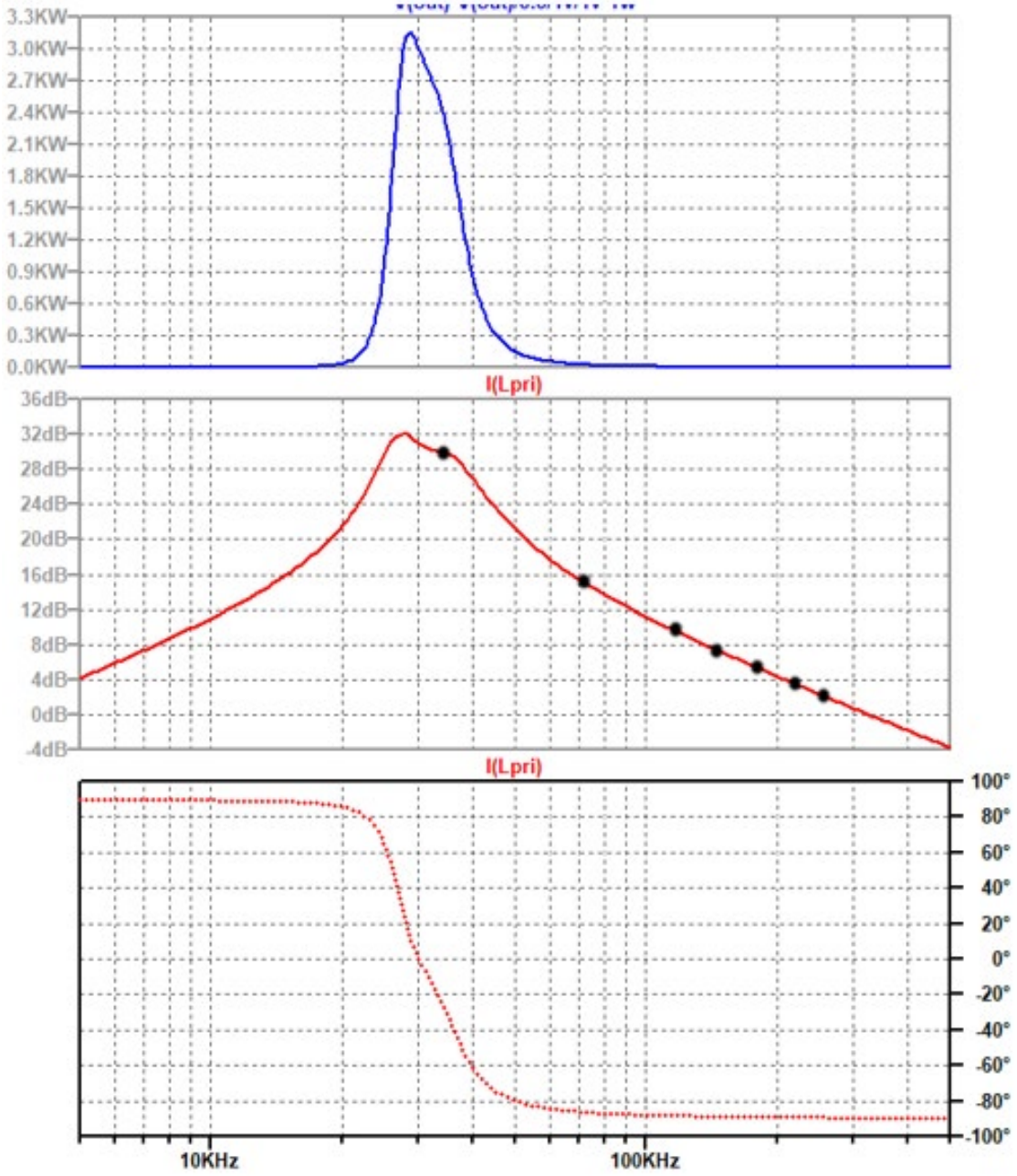


Figure 33: Attenuation of the harmonics by the resonant system in the countertop case

Blue graph shows received power vs operating frequency. To reach the desired power the system has to operate at the right side of the resonance peak. The red graph shows input impedance of the resonating network.

Table 25: Amplitude of the harmonics resonant system in the cooktop case

Harmonic #	Frequency (kHz)	Amplitude (dB)
1	36	29.4
2	72	15.0
3	108	10.3
4	144	7.4

Harmonic #	Frequency (kHz)	Amplitude (dB)
5	180	5.3
6	216	3.7
7	252	2.3

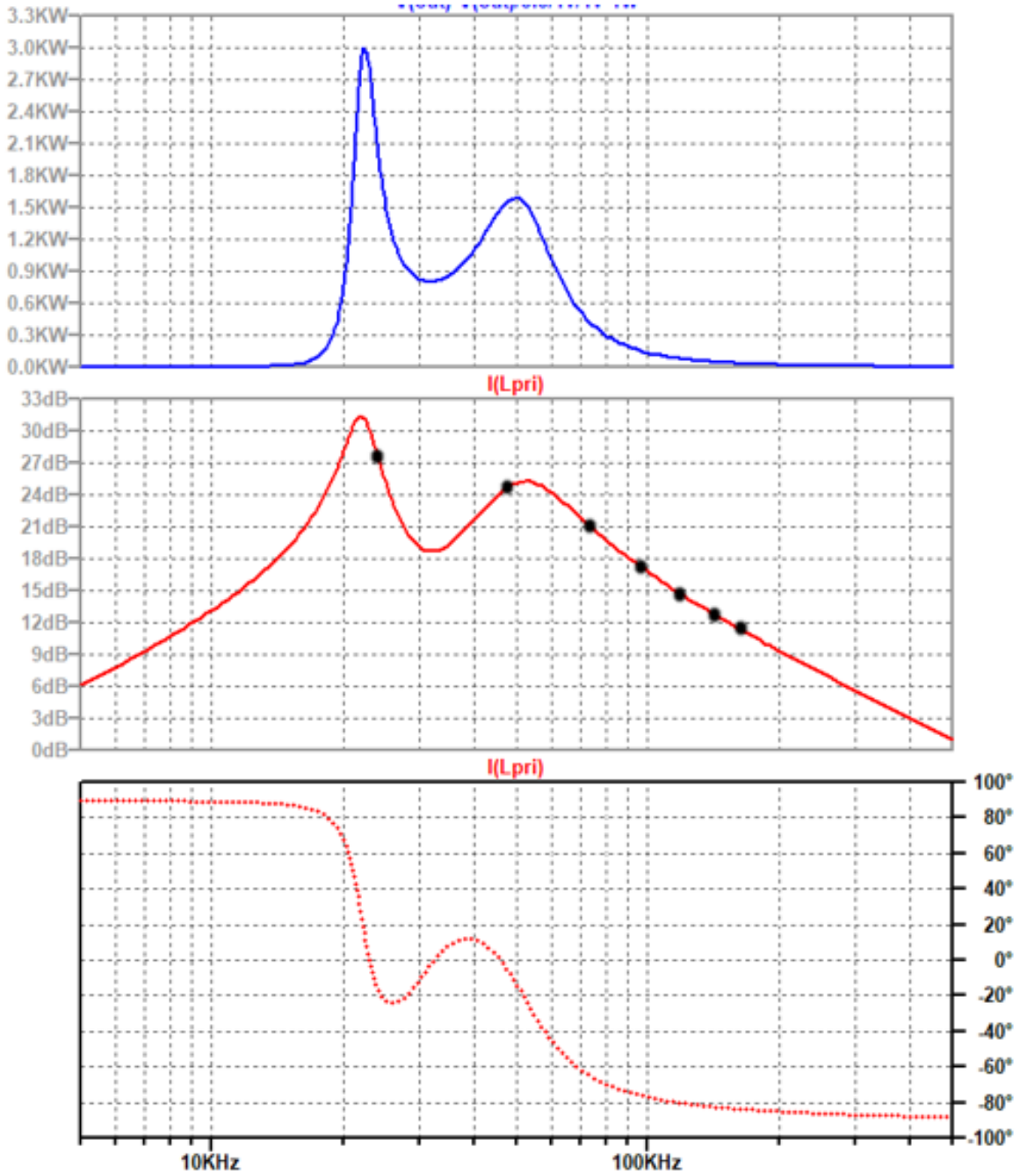


Figure 34: Attentuation of the harmonics by the resonant system in the cooktop case

Blue graph shows received power vs operating frequency. To reach the desired power the system has to operate at the left side of the resonance peak. The red graph shows input impedance of the resonating network.

Table 26: Amplitude of the harmonics

Harmonic #	Frequency (kHz)	Amplitude (dB)
1	24	27.8
2	48	24.8
3	72	21.3
4	96	17.2
5	120	14.6
6	144	12.5
7	168	11.0

Working on the left resonant peak greatly reduces attenuation of higher harmonics relative to the countertop case.

4.4.1.9 Emission Measurements and Conclusion

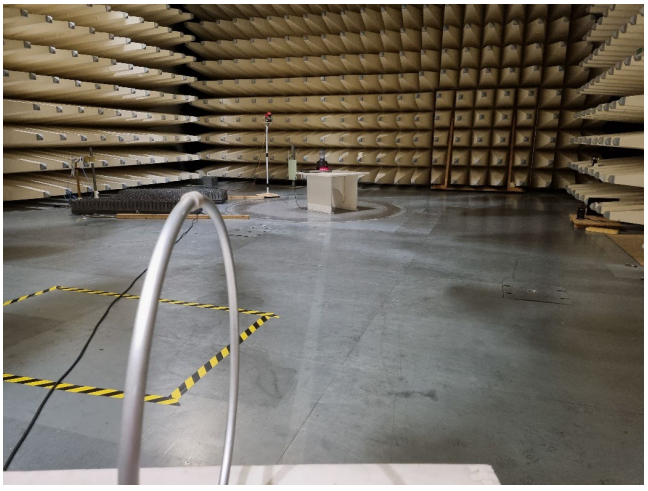


Figure 35: Measurement set up

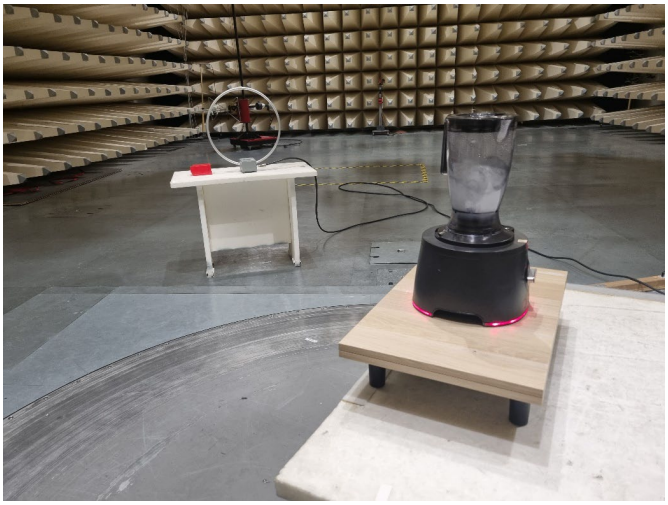


Figure 36: Emission Measurements: Concealed case prototype with blender prototype (200 W)

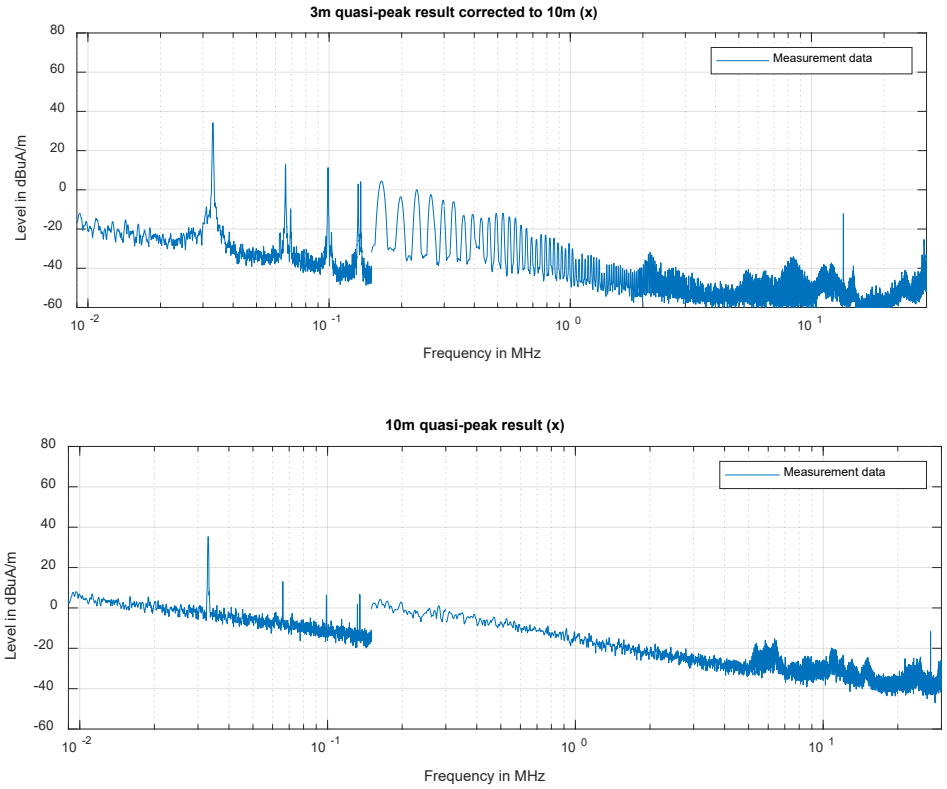


Figure 37: Emission Measurements: Concealed case prototype with blender prototype (200 W)

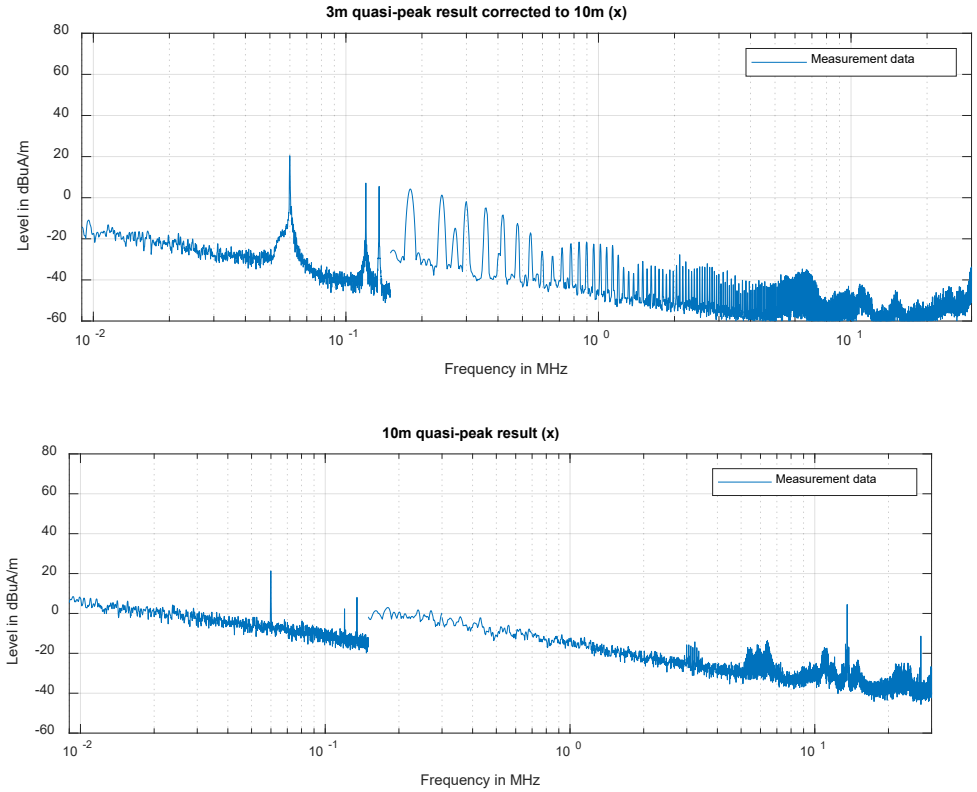


Figure 38: Emission Measurements: Cooktop case prototype with blender prototype (200 W)

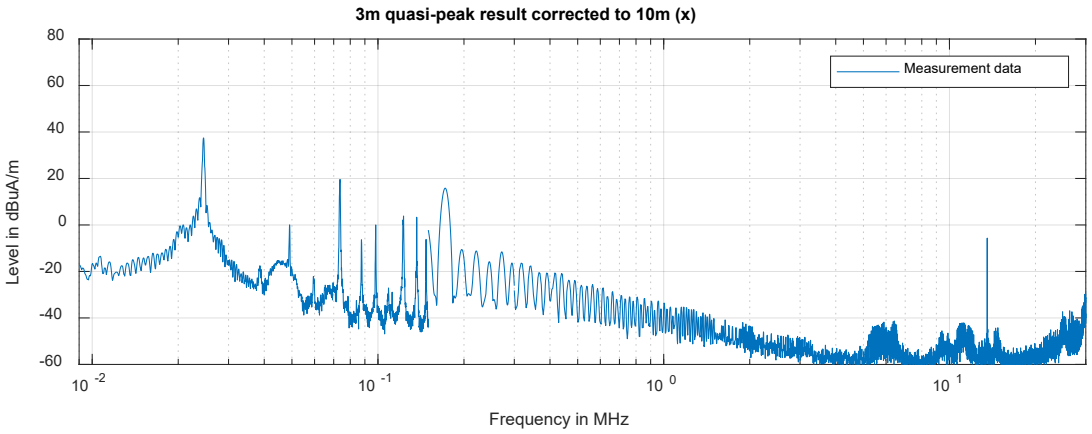


Figure 39: Emission Measurements: Cooktop case prototype with kettle prototype (2.2 kW)

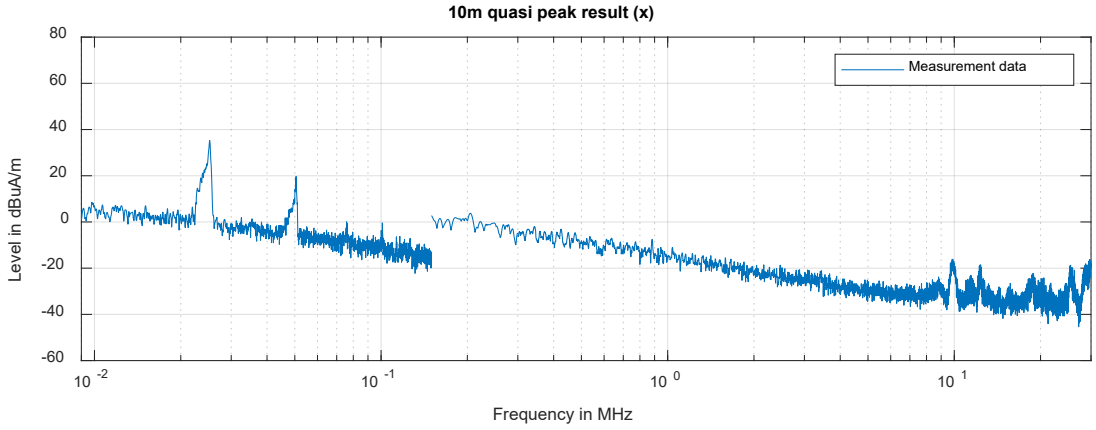


Figure 40: Emission Measurements: Standard induction hob with a pan boiling water (2.0 kW)

Conclusion

Based on simulations and tests conducted on prototype kitchen devices, these WPT systems are multi-frequency systems with necessary harmonic frequency components within the frequency range 20 - 148.5 kHz.

The generated spectrum closely resembles the spectrum generated by existing induction heating systems, of which there are already hundreds of millions in the market.

5 CONCLUSIONS

The main findings of this Report are presented in the Executive summary (Section 0).

ANNEX 1: INFORMATION ABOUT THE RADIO ASTRONOMY SYSTEMS

A1.1 LIST OF LOFAR STATIONS IN THE NETHERLANDS

Table 27 provides the list of LOFAR stations located in the Netherlands.

Table 27: 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 2: LIST OF REFERENCES

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