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EMC Evaluation and Testing for Motorboat

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This Bachelor's thesis includes many of the basic principles and procedures needed to make sure a boat has the required level of electromagnetic compatibility. The information is relevant to both private and commercial boat builders aspiring for electromagnetically problem-free electrical installations.

The thesis begins with basic introduction to electromagnetic compatibility and the different types of interference. Also the standards directing a boat's EMC design and testing have been shortly introduced.

The EMC tests that should be performed to all electrical devices integrated into boats have been described with references to the relevant standards. This information should be useful while choosing devices for a new boat to make sure the devices are electromagnetically compatible. The test procedures are also useful if a boat manufacturer decides to integrate an electrical system of their own design and need to know what types of tests the system needs to pass.

After the compatibility of the individual devices has been ensured, the measures to lower interference in wiring and installation of devices have been depicted for every device group used on board a boat. This is especially useful for the planning of cables, wiring routes and necessary screens.

With the plans ready, a rough EMC evaluation can be made to assess the problematic areas of installation before any part of the boat has been built.

After these phases a seemingly EMI free boat can be built but to make sure everything is fine with the final product a full EMC test should be carried out. The guidelines have been provided for successful EMC tests and the required results.

The tools given in this thesis should be enough to achieve the level of EMC necessary for CE-marking.

Keywords	Boat, EMC, EMI, IEC, CISPR, ICOMIA, EN

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Tämä insinöörityö sisältää tarpeellisimmat keinot ja käytännöt veneen sähkömagneettisen yhteensopivuuden takaamiseksi. Nämä tiedot ovat hyödyllisiä niin yksityisille, kuin myös ammattimaisille veneen rakentajille, jotka tavoittelevat häiriötöntä sähköjärjestelmää veneeseensä.

Insinöörityön alussa kuvataan sähkömagneettinen yhteensopivuus ja siihen liittyvät häiriömuodot pääpiirteittäin. Myös veneen EMC-suunnitteluun ja -testaukseen liittyvät standardit käydään pintapuolisesti läpi.

Jokaiselle yksittäiselle laitteelle valmistajan suorittamat EMC-testit sekä vaaditut tulokset on kuvailtu, jotta asianmukaisten laitevalintojen tekeminen suunnitteluvaiheessa helpottuisi. Jokaisesta testikohdasta löytyy myös viite standardiin, jossa on tarkemmat vaatimukset mittauksille. Näin veneen valmistajan on helpompi löytää tarkat tiedot mittauksista, mikäli veneeseen haluttaisiin asentaa asianmukaisesti testattu venevalmistajan itse suunnittelema sähköjärjestelmä.

Kun yksittäisten laitteiden sähkömagneettinen yhteensopivuus on varmistettu, on vuorossa sähköasennuksien ja johdotusten suunnittelu. Näiden laadukkaan toteutuksen varmistamiseksi jokaiselle erilaiselle laitetyypille on annettu omat ohjeistuksensa häiriöiden vähentämiseksi. Tämä vaihe on erittäin tärkeä etenkin johtoja, johdotusreittejä sekä tarpeellisia suojia suunniteltaessa.

Suunnitelmien toimivuutta voidaan suunnitelmien valmistuttua arvioida karkean EMC-arviointimenetelmän avulla. Näin voidaan puuttua mahdollisiin ongelmakohtiin suunnitelmissa ja korjata ne ennen veneen rakentamista.

Näiden vaiheiden jälkeen rakennetussa veneessä ei pitäisi olla merkittäviä sähkömagneettisia häiriöitä, mutta ennalta arvaamattomien häiriöiden takia on suositeltavaa suorittaa valmiille veneelle täydellinen EMC-mittaus. Tätä varten olennaisimmat tiedot kokonaisen veneen EMC-testeistä on sisällytetty tähän insinöörityöhön.

Näiden tietojen tulisi riittää takaamaan EMC:n osalta vaadittava taso CE-merkintää varten.

Avainsanat	Vene, EMC, EMI, IEC, CISPR, ICOMIA, EN

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Contents

List of Abbreviations

AC	Alternating current
AE	Auxiliary equipment
ALSE	Absorber lined shielded enclosure
AM	Amplitude modulation
CDN	Coupling/Decoupling network
CISPR	International Special Committee on Radio Interference
DAB	Digital audio broadcasting
DC	Direct current
DTTV	Digital Terrestrial Television
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ETSI	European Telecommunications Standards Institute
EUT	Equipment under test
FM	Frequency modulation
GPS	Global positioning system
GSM	Global system mobile
ICOMIA	International Council of Marine Industry Associations
IEC	International Electrotechnical Commission

ISO	International Organization for Standardization
LW	Long wave (amplitude modulated)
MW	Medium wave (amplitude modulated)
OTS	Outdoor test site
RBW	Resolution bandwidth
RC	Resistor & Capacitor
RF	Radio frequency
RFI	Radio frequency interference
RKE	Remote keyless entry
SW	Short wave (amplitude modulated)
SWR	Standing wave ratio
UHF	Ultra high frequency (frequency modulated)
VHF	Very high frequency (frequency modulated)

1 Introduction

Electromagnetic interference is an electrical phenomena that affects every conductive circuit created. This is also the case with boats. Boats are very dependent on variety of radio and navigation devices on board to make navigation at waters safer. The amount of different equipment required for the task brings forth possibilities of electrical disturbances. The science to diminish the disturbances is called EMC.

Electromagnetic compatibility is one of the things that no one notices when it has been taken care of properly but becomes a very unpleasant factor if done wrong. EMC should be kept in mind from the beginning of a design process for any vehicle as it is very hard and expensive to fix the interference after the vehicle is finished.

To help prevent unnecessary risks due to EMC this document has been produced to help boat builders assess the level of EMI in their boats and show how a boat's conformity to the necessary standards can be validated. The contents are relevant to both commercial and private builders for any boat operating with the help of electrical devices. The scope of this document is limited to vessels below 24 meters in length, if not otherwise stated. There is no differentiation between boats with open construction and ones with a cabin.

The material from this document is gathered from various official standards, regulations and recommendations to ease the EMC design of a boat. Following the steps described should be enough to attain document of conformity i.e. CE-markings in regards of EMC. However it is advisable to get acquainted with the official documents and verify that everything matches with local regulations. The manufacturer of a boat is the one responsible for making certain every requirement is met.

2 EMC

When a mobile phone is left in close proximity to an old speaker, incoming phone call induces noise in the speaker. This is called electromagnetic interference also known as EMI. The reason this noise can be heard is due to poor electromagnetic compatibility of the speakers. EMC is an electrical science dedicated to lower electrical device's electromagnetic emissions and improve the immunity for these emissions.

2.1 The different types of EMI

The types of interference are conducted, inductive, capacitive and radiated. Conductive interference is conducted through physically connected coupling. Badly designed earthing or inadequate wire dimensions can produce conductive interference to other nearby circuits (Ott 2009: 31–33). Inductive interference is created by magnetic field induced by rapid change in current inside a wire. Loops in wiring work as inductors and efficiently pick up these changes in magnetic field. (Ott 2009: 52, 53.) Capacitive interference happens when unshielded cables with high impendence are in close proximity to each other and work like capacitors broadcasting the signal to other cables nearby through electric field (Ott 2009: 45, 46). Radiated interference originates usually from high frequency (>50 MHz) antennas used for radio, television and mobile phone transmissions (Ott 2009: 546). Also many transient natural phenomena like lightning and solar flares produce strong RFI (Ott 2009: 557). The ways of interference coupling are illustrated in figure 1.

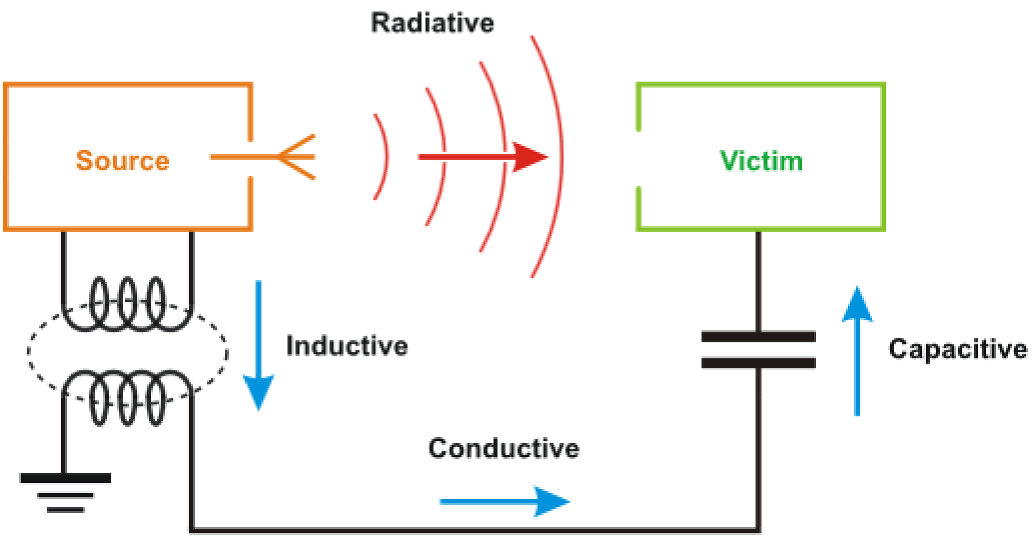


Figure 1. The four ways of EMI coupling are conductive, inductive, capacitive and radiative interference. (Electromagnetic compatibility 2015.)

2.2 Near-field and far-field interference

All devices with conductive circuitry are naturally vulnerable to EMI. If the circuitry is in close proximity to other electronics it is exposed to interference through conduction as well as magnetic and electric fields. These are called near-field interference and are measured separately. Far-field interference happens at radio frequencies and is dominant source of interference when moving further away from the source. Far-field interference consists of both magnetic and electric field interference but no separation is made between them at these far-field distances. (Ott 2009: 33.)

The classification of interference to near-field and far-field interference is dependent on the frequency of transmission and the distance between interference source and receiver. At lower frequencies the wave length of transmission is long and leads to long near-field area where as higher frequency with shorter wave length means smaller near-field area. The wave length of a signal in free space can be calculated with formula (1).

$$\lambda = \frac{c}{f} \tag{1}$$

λ is wave length in meters, *c* is the speed of light (approximately 299 792 458 m/s) and *f* is the frequency used. The transition point of near-field to far-field can be calculated with formula (2).

$$\frac{\lambda}{2\pi} \tag{2}$$

If the distance from broadcasting device is less than the result from formula (2), the area in question is near-field and vice versa if the distance is more than the result the operation happens in far-field. (Ott 2009: 238–240.)

2.3 Electromagnetic interference's effects on electrical equipment

EMI's severity to equipment's operation depends on the susceptibility of the device and strength of interference. The less significant interference may appear as audible noise from speakers or visual noise on screen. These are an inconvenience to the user and a sign of lacking EMC design. Critical error in EMC design might lead to device going into safe mode or reboot. In vehicle such a malfunction is dangerous and might impair navigation or even vehicle controls. In worst case EMI might be so powerful it ends up compromising a device and making the vehicle unusable.

2.4 Shielding from EMI

There are three ways to decrease the effectiveness of electromagnetic interference. They are mitigating the interference, shielding from it and severing the route of interference. Many mathematical formulas exist to help EMC design but due to many variables in operating environment everything can't be taken into account by simulations. In many cases experience is very important to achieve a properly working design.

Electrical devices' cabling has a big impact on both capacitive and inductive interference. Many unshielded wires tied closely together work as capacitors to each other and let interference move from one wire to other. Also large loops in wiring are favorable for interferences caused by dynamic magnetic fields. Shielded wiring grounded in both ends should be used as often as possible to lessen interference and especially in critical signal wires to dispel signal alterations. (Ott 2009: 44)

Devices' grounding becomes a weak point when interference in unintended frequency band is introduced to grounding wire that hasn't been designed to ground such a load. The designing of a good grounding relies very much on previous experience because multiple grounding solutions exist for different kinds of loads. Other problems with grounding are too small wires and badly designed grounding routes. These usually lead to seemingly random faults in the device's operation. (Ott 2009: 120–132.)

Devices can be made more resistant to conducted interference in specific frequency bands with the implementation of filters (Ott 2009: 174). Another way to lessen interference is to use decoupling capacitors to decrease current alterations during transient situations (Ott 2009: 178, 179).

Casing is also an important part of good EMC design. A metallic inner casing can work as Faraday's cage that isolates electrical fields both inside and outside the casing. Right materials also dampen EMI by absorbing and reflecting parts of its energy. (Ott 2009: 243).

2.5 Boat's operational environment

The environment a boat operates in should be considered while making EMC designs as it differs by a large margin from land based conditions. Boat is closest to other interference sources while docked, but even so power lines and residential areas are usually at least half a kilometer away (IEC 60945 2002: 157). Other boats could send interference while at port but due to EMC requirements set for boats it is very unlikely. Except for transient natural phenomena the strongest source of interference is from boat's own equipment and wiring.

A boat should have a proprietary grounding route for lighting strikes to avoid any damage to equipment and personnel. At sea a boat is the easiest route for lightning to ground due to metallic mast, structures and antennas. Failing to route lightning's energy away from electrical equipment could have disastrous consequences at sea. (Becker 1985.)

2.6 Regulating documents for boat's EMC

Standards are the backbone of EMC and contain most of the necessary information to design acceptable electrical system. The following standards are most important to design boat's electronics and EMC. Only the up to date versions of these standards should be used.

2.6.1 IEC 60945

Maritime navigation and radiocommunication equipment and systems – General requirements – Methods of testing and required test results

IEC 60945 contains general requirements for navigation and radio equipment with EMC test procedures and requirements. Any marine electrical device on board a boat should be compliant to this standard.

2.6.2 CISPR 12

Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of off-board receivers

CISPR 12 contains the EMC test procedures and requirements for any boats propelled by means of internal combustion engine, electric motor or both. The requirements are for permissible interference produced by the boat at a measuring distance of 10 m.

2.6.3 CISPR 25

Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers

The contents of CISPR 25 provide guidelines to measuring radiated interference from within the boat that may affect other devices on board the boat through antenna reception.

2.6.4 IEC 60533

Electrical and electronic installations in ships – Electromagnetic compatibility

IEC 60533 focuses on general EMC requirements for boat's electrical equipment installations but also contains recommendations to achieve necessary level of EMC. It also gives guidance to rough EMC evaluation based on equipment data, wiring routes and mounting positions.

The aforementioned standards are based on more general EMC standards but should be clear enough for anyone with ample understanding of electrical engineering and EMC.

2.6.5 Recommended material

A recommended guide compiled by ICOMIA for boat's EMC is *ICOMIA Recommended Practice on EMC Testing.* It has been especially targeted for private boat builders with limited budget for EMC testing.

2.7 The organizations

The bodies regulating EMC in maritime environment include both Electrical standards organizations and marine standards organizations. International Electrotechnical Commission (IEC) is a standards organization focusing on all electronics and related technologies (Welcome to the IEC 2014). European Telecommunications Standards Institute (ETSI) is an internationally acknowledged standardization organization for information and communications technologies (About ETSI 2015). International special committee on radio interference CISPR produces standards for radio reception protection in the frequency range between 9 kHz and 400 GHz (CISPR Scope 2015). CISPR is among other things responsible for standards concerning radio interference measurements done to vehicles equipped with internal combustion engines, electrical motors or hybrids of aforementioned propulsion systems. International Council of Marine Industry Association (ICOMIA) is not a standards organization but it has had a major part helping create multiple ISO standards and guidelines for small crafts (International Council of Marine Industry Associations 2014).

3 EMC tests for individual device

All commercially available electrical devices have to be tested for EMC to fulfill CE-markings requirements. A boat should be electromagnetically compatible if every non-benign electrical device used aboard the boat meets the requirements set in IEC 60945 and the electrical installations have been made with proper engineering practices. Nonetheless EMC tests are recommended due to possible unforeseen problems occurring.

3.1 Non-benign equipment

Not all the equipment aboard a boat are susceptible to EMC so it is important to know when a device should be EMC tested. As boat’s manufacturer should already have a list of all equipment on board the boat it should be easy to check whether a device is benign or non-benign. For example batteries and wires are naturally considered benign equipment by themselves but installation of the aforementioned equipment is susceptible to interference. The following list contains typical devices aboard a boat that are non-benign and require individual EMC testing. (ICOMIA Recommended practices on EMC Testing 2013: 13)

- Battery charger and or inverter
- Horn
- Windshield wiper motor
- Propulsion trim pump
- Electric hatch lift
- Bilge pump
- Bilge blower
- Fresh water pump
- Windlass
- Electronic toilette items (vacuum pump, macerator, etc.)
- Electrical thruster motors, bow/stern
- LED, low energy and fluorescent lighting (includes interior and navigation) (tungsten filament and
- halogen lighting is benign)
- Helm electronics (radar, autopilot, chart plotter, depth sounder, sonar)
- Stereo and associated equipment
- All radio equipment
- TV amplifier (NOTE passive antennae are considered benign equipment)
- Trim tabs
- Engines
- Refrigerator/freezer/ice maker/wine chiller and other compressor driven appliance
- Any type of information technology equipment (personal computers, network connection equipment, video displays, multimedia products etc.)

EMC test results should be inquired from the device's manufacturer and compared to the requirements in IEC 60945.

3.2 Device without adequate EMC test results

If a device does not have adequate EMC test results from manufacturer the options are either to find a surrogate device with proper EMC capabilities or have the EMC tests made by an EMC testing establishment according to IEC 60945 standard. The first option is recommended due to the extra expenses involved in unnecessary EMC tests. In case the latter option is chosen the test procedures and required results are described according to IEC 60945 fourth edition 2002-08.

3.3 Test procedures

Full compliance EMC tests for individual equipment should be done by professional testing organization with necessary equipment and facilities for the tests. This is usually the device manufacturer's responsibility and they should be able to provide the testing data when inquired to.

All the tests have to be carried out in suitable testing facility arrangement (figure 2). The full specifications of such facility are described in CISPR 16-1 from which all the necessary testing arrangements and equipment can be found.

The distance between EUT and antenna is 3 m and applies to all tests with radiated emissions or immunity (IEC 60945 2002: 91). The limit for radiated emission and immunity test is at 2 GHz even though boats may carry devices operating at super high frequency band (3–30 GHz). It is not necessary to measure above 2 GHz due to no evidence showing EMC problems for these frequencies where very directional antennas are used (IEC 60945 2002:163). The general test procedures are described below for each sub-test, but these are not all inclusive instructions. The IEC 60945 standard contains all the necessary information for tests and should be used as the reference material for EMC tests performed by authorized facility.

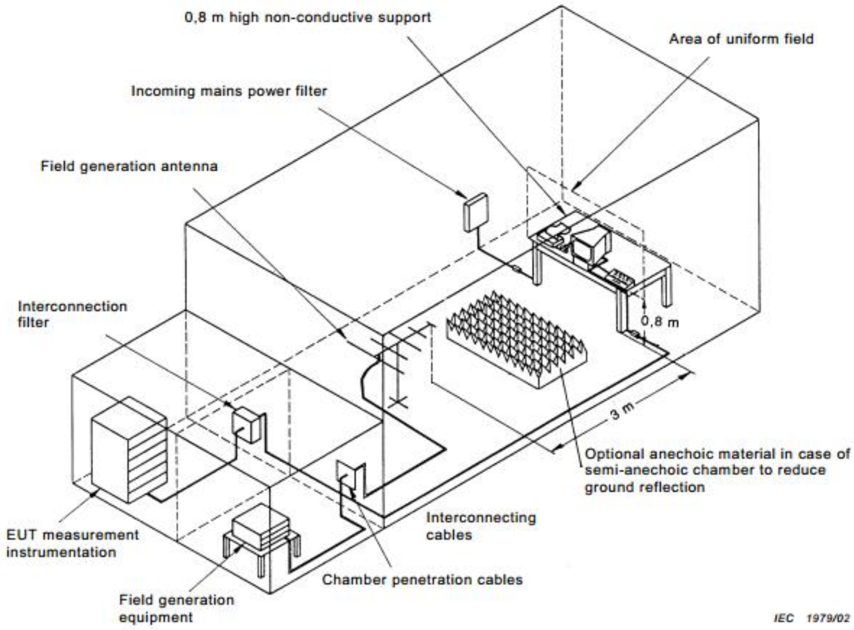


Figure 2. An example of a testing facility arrangement for radiated emission and immunity tests. (IEC 60945 2002: 127.)

3.4 EMC test plan

Before EMC tests it is imperative to establish a test plan that includes all the necessary information about the tests. With proper test plan the testing will be straightforward and no problems should occur. The following information should be stated elaborately.

- assembly of EUT and reasoning behind it
- EUT interconnecting cables
  - multiple cable types should be tested if possible
- list of auxiliary equipment
- cabling and grounding
- operational conditions
- environmental conditions
  - temperature should be between +15 ^{o}C and +45 ^{o}C
  - relative humidity should be between 20 % and 75 %

- test software
- acceptance criteria according to 3.7
- each subtest to be performed during EMC test

(IEC 60533 1999: 14, 15.)

3.5 EMC test report

The EMC test report should contain all the information from the EMC test plan and all the test results accurately and objectively. Every deviation from the test plan should be clearly reported. (IEC 60533 1999: 19.) The report should also contain the following information:

- sample identification
- date and time of test
- bandwidth
- step size
- required test limit
- ambient data

(CISPR 25 2008: 15.)

3.6 Electromagnetic emissions

Emissions refer to any interference sent by the equipment under test whether it’s radiated or conducted. Radiated interference refers to inductive, capacitive and radiative emissions occurring without physical contact or through antenna. Conductive emissions are unwanted signals appearing in device’s power supply port from where they can proceed to interfere with other equipment in the boat. (IEC 60945 2002: 87.)

The objective of the test is to find the maximum emission values under normal operating conditions. The variables to be taken into account are controls which may affect emissions and whether the device under test has multiple energized states. Measurements should be made to ascertain the settings emitting most interference and then full tests run with these settings. It should be noted that radio transmitters should not be in transmitting state while being tested. If the EUT has antenna connection, the corresponding port should be terminated using a non-radiating artificial antenna. (IEC 60945 2002: 87)

3.6.1 Conducted emissions

Conducted emissions are to be measured with a quasi-peak measuring receiver from device's input power cables. A suitable test setup has to be used to have known impedance between the EUT's terminals and to isolate possible radio frequency interference. An example composition of mains network can be seen in figures 3 and 4. Specifications for the measuring receiver and the composition of the test setup can be found in CISPR 16-1. (IEC 60945 2002: 89.)

The tests are separated to frequency ranges from 10 kHz to 150 kHz with measuring bandwidth of 200 HZ and 150 kHz to 30 MHz with measuring bandwidth of 9 kHz. The power cables between the device and mains network should not exceed 0.8 m in length. In case of a device consisting of multiple units and more than one of these units having its own power port with identical nominal voltage, the power cables should be connected parallel to the mains supply network. The device should be mounted and attached on an earth plane. (IEC 60945 2002: 89.)

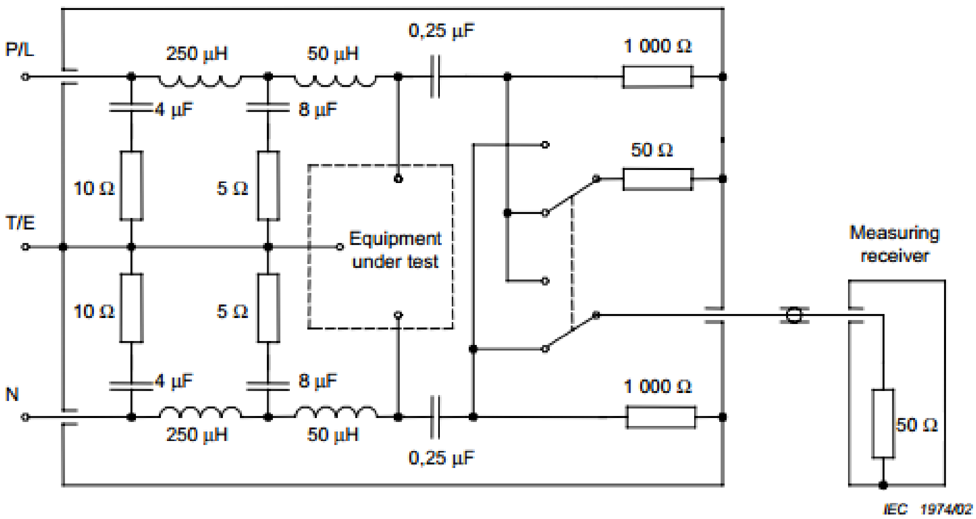


Figure 3. Example of an artificial mains V-network to use for measurements in frequency range of 10 kHz to 150 kHz. (IEC 60945 2002: 119.)

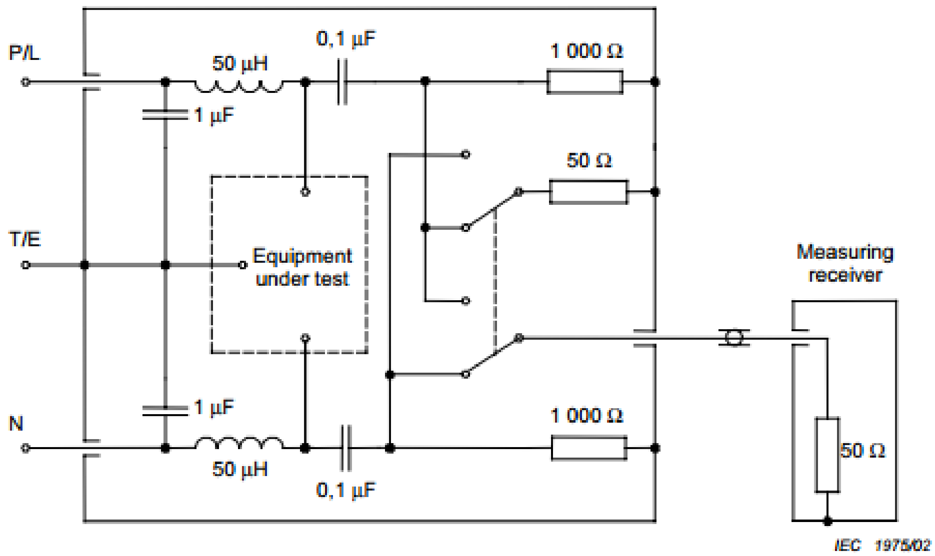


Figure 4. Example of an artificial mains V-network to use for measurements in frequency range of 150 kHz to 30 MHz. (IEC 60945 2002: 119.)

The test requirements for conducted emissions in frequency range of 10 kHz to 30 MHz can be seen in figure 4. The allowed emission levels are lower than immunity limits to ensure correct operation at all times. (IEC 60945 2002: 89.)

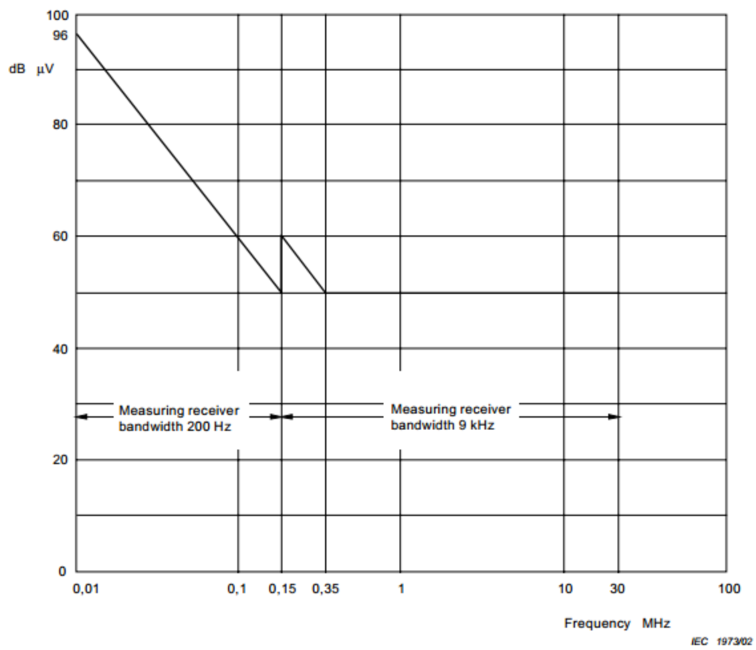


Figure 5. The test result limits between frequency ranges of 10 kHz to 30 MHz. (IEC 60945 2002: 117.)

3.6.2 Radiated emissions

Radiated emissions will be separated into two frequency bands. First is the magnetic field between 150 kHz and 30 MHz with receiver bandwidth set at 9 kHz. For this measurement an electrically screened loop antenna, which can fit in a square with sides of 60 cm, is used. For precise specifications of the antenna refer to CISPR 16-1. To have the results in equivalent electric field strength values, the antenna has to be used with a correction factor of 51,5 dB. (IEC 60945 2002: 91, 93.)

The second frequency band is from 30 MHz up to 2 GHz with receiver bandwidth set to 120 kHz. Also a second test should be run with alteration between frequency bands of 156 MHz to 165 MHz by setting the receiver bandwidth at 9 kHz. These measurements are for electric fields and do not require any correction factors. The antenna used is a dipole model with specifications described in CISPR 16-1. The center of the antenna should be 1,5 m above ground until 80 MHz and after that measurements should take place to determine the height between 1 m and 4 m for the highest emission readings. The EUT should also be rotated on the plane it is placed on to find the angle with most emissions. If this cannot be done then the antenna can be moved correspondingly while maintaining the set distance from the EUT. The EUT should be otherwise set up similar to the final installation in a boat. (IEC 60945 2002: 91, 93.)

The limits for test results from 150 kHz to 2 GHz can be seen in figure 5. For the second test the radiation limit between 156 MHz to 165 MHz is 24 dBµV/m. (IEC 60945 2002: 91, 93.)

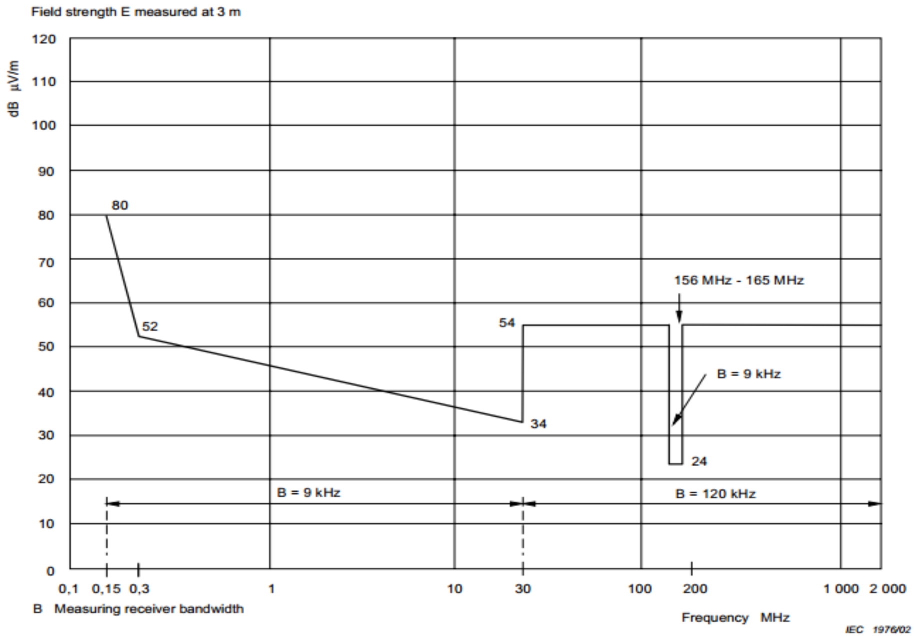


Figure 6. The radiation limits for EUT's radiated emissions. (IEC 60945:121)

3.7 Electromagnetic immunity

Electromagnetic immunity is tested to measure device's capability to operate under conducted and radiated interference as well as electrostatic discharge. During these tests the EUT is installed as it would be when operational in a boat. Three different performance criteria are used for the measurement results as shown in table 1.

- Performance criterion A: the EUT shall continue to operate as intended during and after the test. No degradation of performance or loss of function is allowed, as defined in the relevant equipment standard and in the technical specification published by the manufacturer

- Performance criterion B: the EUT shall continue to operate as intended after the test. No degradation of performance or loss of function is allowed, as defined in the relevant equipment standard in the technical specification published by the manufacturer. During the test, degradation or loss of function or performance which is self-recoverable is however, allowed, but no change of actual operating state or stored data is allowed.

- Performance criterion C: temporary degradation or loss of function or performance is allowed during the test, provided the function is self-recoverable, or can be restored at the end of the test by the operation of the controls, as defined in the relevant equipment standard and in the technical specification published by the manufacturer.

(IEC 60945 2002: 93, 95.)

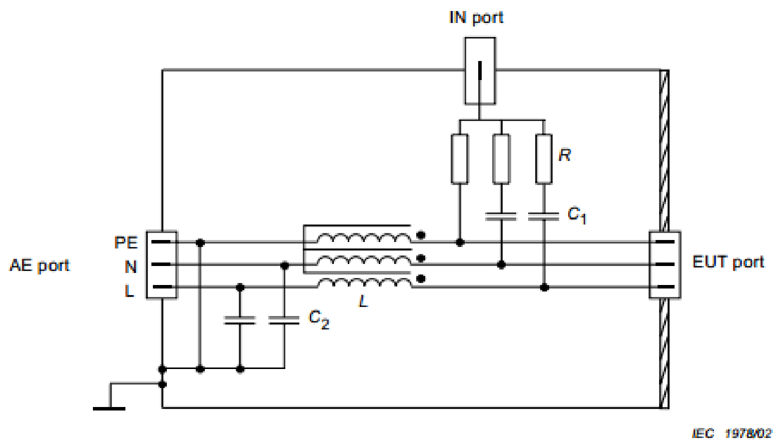
Table 1. Summary of all the tests and criteria used for different immunity measurements. (IEC 60945 2002: 95.)

	Portable	Protected	Exposed	Submerged
Conducted radio frequency disturbance (IEC 60945 Clause 10.3)	*	Performance criterion A		
Radiated disturbance (IEC 60943 Clause 10.4)	Performance criterion A			*
Fast transients (bursts) (IEC 60943 Clause 10.5)	*	Performance criterion B		
Slow transients (surges) (IEC 60943 Clause 10.6)	*	Performance criterion B		
Power supply short term variation (IEC 60943 Clause 10.7)	*	Performance criterion B		
Power supply failure (IEC 60943 Clause 10.8)	*	Performance criterion C		
Electrostatic discharge (IEC 60943 Clause 10.9)	Performance criterion B			*
* not applicable				

3.7.1 Conducted immunity

The device's ability to stand interference through power, signal and control lines is evaluated in conducted immunity test. The EUT is placed on a 0,1 m high insulating support above ground reference plane and connected to all necessary auxiliary equipment (AE) to achieve same functionalities as in real installation in a boat. Coupling and decoupling devices (CDN), shown in figure 7, are placed 0,1 m to 0,3 m away from the EUT. CDN is placed between EUT and AE cables to provide a known impedance and prevent interference from affecting the AE. The interference generator is connected to every CDN one by one while the RF input ports not used are terminated by a 50 Ω load resistor. The EUT and AE should be disconnected and substituted with 150 Ω resistors while the interference generator is being connected to the CDN. (IEC 60945 2002: 97.)

The test should be run with unmodulated 3 V_{rms} amplitude from 150 kHz to 80 MHz. Also higher amplitude of 10 V_{rms} should be used in the following frequencies: 2 MHz, 3 MHz, 4 MHz, 6,2 MHz, 8,2 MHz, 12,6 MHz, 16,5 MHz, 18,8 MHz, 22 MHz, 25 MHz. (IEC 60945 2002: 97.)



NOTE CDN-M3, C_1 (typ) = 10 nF, C_2 (typ) = 47 nF, R = 300 Ω, $L \geq 280$ µH at 150 kHz.
CDN-M2, C_1 (typ) = 10 nF, C_2 (typ) = 47 nF, R = 200 Ω, $L \geq 280$ µH at 150 kHz.
CDN-M1, C_1 (typ) = 22 nF, C_2 (typ) = 47 nF, R = 100 Ω, $L \geq 280$ µH at 150 kHz.

Figure 7. An example of simplified CDN construction used in conducted immunity tests. (IEC 60945 2002: 125.)

To pass the test the EUT should fulfill the requirements of performance criterion A during and after the tests (IEC 60945 2002: 97).

For more detailed test specifications refer to IEC 61000-4-6 standard.

3.7.2 Radiated radiofrequency immunity

The purpose of this test is to assure the EUT can work in close proximity to portable and on board radio transmitters operating in frequency range of 80 MHz to 2 GHz without issues. During the tests the EUT should be placed on insulating support and connected with cables according to the manufacturer. If the manufacturer has not specified cabling, unshielded parallel wires are used and placed 1 m from the EUT. The measurements are carried out for every four sides of the EUT at 10 V/m field strength from 80 MHz to 2 GHz frequencies. The sweeping rate used for frequency range from 1 GHz to 2 GHz is one third of the sweeping rate used for 80 MHz to 1 GHz range. The electric field should be modulated at 400 Hz ± 10 % to a depth of 80 % ± 10 %.

The EUT should remain operational throughout and after the test according to performance criterion A to pass the test (IEC 60945 2002: 97, 99).

For more detailed test procedures refer to IEC 61000-4-3 standard.

3.7.3 Fast transient interference immunity

Fast switching in electrical device produces voltage oscillations and possible arching in the switching component. During this oscillation current is bouncing back and forth producing conducted interference through connected cabling and radiated interference by means of alternating electromagnetic field. The device's level of immunity for power, signal and control ports is measured with fast transient interference test. The test takes 3 to 5 minutes and every 300 ms a burst of 15 ms is produced into the measured device's cable. During the burst for AC power lines a pulse with amplitude of 2 kV and frequency of 2,5 kHz is produced into the cable. For signal and control lines a pulse with amplitude of 1 kV and frequency of 5 kHz is used instead to imitate coupling from power lines. The pulse is very fast with width of 50 ns and rise time of 5 ns. For accurate test procedure refer to IEC 61000-4-4 standard.

The EUT should meet the requirements of performance criterion B during and after the test (IEC 60945 2002: 99, 101).

3.7.4 Immunity to power line surges

The objective of power line surge immunity test is to make sure a slow, high-energy surge produced by thyristor switching on AC power supply does not cripple the device. During the 5 minute test a pulse with amplitude of 1 kV for power lines and 0,5 kV for signal or control lines is produced into the line at the rate of 1 pulse per minute. The pulse is 50 µs in length and has a rise time of 1,2 µs. The test procedure is described in its entirety in IEC 61000-4-5 standard.

The EUT should perform at least in the level of performance criterion B during and after the test to pass (IEC 60945 2002: 101).

3.7.5 Power supply short-term variation immunity

During the test EUT's ability to cope with power supply variations caused by changes in load is measured. This test is only applicable to AC-powered devices. For the test a programmable power supply is used to produce variations into the power line once per minute for the duration of 10 minutes. The variations alternate between the following values, also depicted in figures 8 & 9. For further information about the test refer to IEC 61000-4-11 standard. (IEC 60945 2002: 101, 103.)

- Nominal voltage + (20 ± 1) %, duration 1,5 s ± 0,2 s

  Nominal frequency + (10 ± 0,5) %, duration 5 s ± 0,5 s

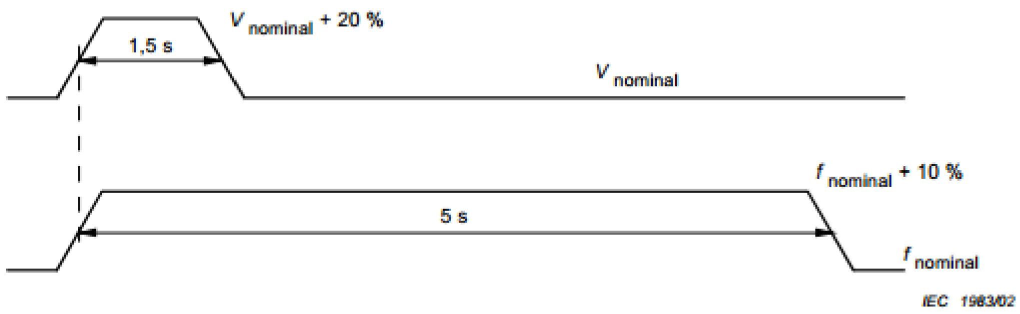


Figure 8. Positive variations in power lines. (IEC 60945 2002: 133.)

- Nominal voltage - (20 ± 1) %, duration 1,5 s ± 0,2 s

  Nominal frequency - (10 ± 0,5) %, duration 5 s ± 0,5 s

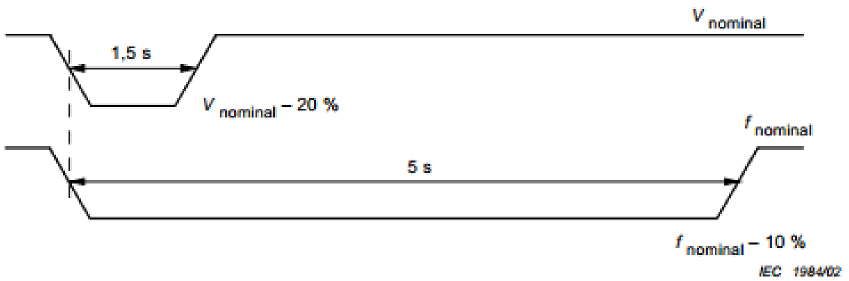


Figure 9. Negative variations in power lines. (IEC 60945 2002: 133.)

During and after the test EUT should operate at the level described in performance criterion B (IEC 60945 2002: 103).

3.7.6 Immunity to power supply failure

This test is not applicable to devices equipped with their own batteries as it simulates short breaks in boat's own power supply in case of power supply changeover and breaker drop-out. During the test EUT is exposed to three breaks in power supply each lasting for 1 minute. The full description of test procedure can be found in IEC 61000-4-11. (IEC 60945 2002: 103.)

The EUT should perform according to performance criterion C during and after the test with no corruption in software or loss of essential data (IEC 60945 2002: 103).

3.7.7 Immunity to electrostatic discharge

Humans can easily be electrostatically charged in right conditions up to many kilovolts. If such a voltage discharges through a badly designed device it may cause a malfunctions or breakdown in the affected device. The purpose of electrostatic discharge immunity test is to make sure the device can operate as intended after the discharge has coupled through the circuitry. For the test an ESD generator with energy storage capacitance of 150 pF and discharge resistance of 330 Ω is used. The EUT is placed on, but insulated from, a metal ground plane that stretches at least 0,5 m beyond all the EUT’s sides. The ESD generator is placed perpendicular to the surface and the places from where the discharges take place are explored while using 20 discharges per second. The discharges are only applied to those points in the EUT that personnel may be in contact during normal operation. For each position found 10 additional positive and negative discharges are produced in intervals of at least 1 second to observe any malfunctions in the device. Contacted discharges at 6 kV are preferred but if not possible due to insulating paint for example, air discharges at 8 kV are also acceptable. For more detailed test procedures refer to IEC 61000-4-2. (IEC 60945 2002: 103, 105.)

The EUT should be able to perform according to performance criterion B during and after the test (IEC 60945 2002: 105).

4 Installation and cabling

Electrical installations’ electromagnetic compatibility is also a critical aspect to consider while designing a boat. Different devices’ EMC properties should be well considered while designing installation locations to avoid easily disturbed device being next to a highly radiative device. Cables and wiring routes should also be carefully planned to avoid interference coupling through wiring. Low level signal wires should be kept separate from power wires. Ground potential is also very important part of installation design since it both makes sure electrical equipment are working in same potential without interference and that there are no metallic surfaces on boat with different voltage potentials leading to danger for the crew. (IEC 60533 1999: 32, 33.)

While planning the installations, the means to lower EMI are to prevent the interference from coupling to susceptible equipment, reduce the emission levels from the source and improve the level of immunity at affected devices. The device groups found on a boat have been divided to seven classes and based on the class’s properties proven methods have been provided to avoid unnecessary EMI using the aforementioned methods. (IEC 60533 1999: 33.)

4.1 General screening methods

4.1.1 Grounding

The objective of grounding is to provide unified ground potential to all devices and make sure there are no voltage differences within the boat’s conductive surfaces. The devices can be grounded using two different methods. In a star pattern grounding connection the devices have one shared grounding point or as other option each device may be grounded using grounding plane i.e. each device is grounded by proprietary grounding point. The difference of each grounding type is in frequency limits. The star pattern should be used when AC and DC frequencies are below 10 kHz and grounding plane when frequencies are above 100 kHz. For the remaining frequency band either of the options may be used but grounding plane is the preferred choice. The grounding connections should be made as short as possible to have small inductance and the wires used should have as low high-frequency impedance as feasible. The connections should also be resistant to corrosion and vibrations so the grounding impedance doesn’t increase over time due to wire and contact point degradation. All the grounding contact points should be clean of any insulating paints and materials to achieve the best grounding. Applying contact protection spray or paste to all contact points is recommended before final assembly. Easy accessibility to grounding points is also advisable to ease routine inspections. (IEC 60533 1999: 34.)

Grounding doesn’t only concern electrical equipment but also any insulated conducting object should be brought to ground potential with good electrical connection. Corrosion resistant solid or flexible steel wires are recommended on deck. By doing this there is no possibility of interference through undefined bonding and the crew is safe from electric shocks due to different voltage potentials. Grounding is critical for correct operation of electrical equipment as well as non-electrical conducting equipment so it is advisable to have as many grounding connections as feasible for all affected cable screens, surfaces and enclosures. (IEC 60533 1999: 34, 35.)

In case of a boat with non-metallic structure an artificial ground is formed by all interconnected metal parts (IEC 60533 1999: 35).

4.1.2 Cable routing

Device manufacturer's installation requirements concerning cable selection and routing should always be followed by default. It is advisable to run wires always near metallic structures or on metallic cable trays. The cables can be divided into categories, as shown in appendix 1 table 1, based on the carried signals and bundled accordingly. This way also the bundles can be spaced accordingly to prevent highly disruptive cables from affecting delicate signal wires. For cables or cable bundles from different categories which run in parallel for more than 1 m should be installed with a spacing of at least 10 cm. This rule also applies to cables from same category with differing signal levels. Cables from categories 1, 4 and 5 should be well fastened to a metal surface on the boat such as deck, bulkhead or cable duct. (IEC 60533 1999: 35.)

Where minimum cable separation limit cannot be adhered to or category 3 and 4 cables are nearby, special protective measures like protective cable piping or wires with high shielding effectiveness should be used. The cable piping should have a thickness of at least 1 mm if not otherwise specified. (IEC 60533 1999: 36.)

4.1.3 Interference filtering and overvoltage protection

Filters and overvoltage protection components reduce effectively conducted interference without distorting the signal or carried power. To reduce the costs of filters and overvoltage protection components, it is advisable to only apply them based on emission or susceptibility levels. If only few devices emit high levels of interference, their outgoing signal should be filtered and vice versa if only few devices suffer badly from interference, their incoming signal should be filtered. (IEC 60533 1999: 37.)

Power supplies use either DC or AC at 50, 60 or 400 Hz which leads to the use of low-pass filters in power lines. This means that signals only pass through the filter when their frequency range is below the filter's designed pass limit. It should be kept in mind that utilization of filters brings forth insertion losses in the wires. Other criteria to consider when choosing filters are:

- Attenuation band
- Number of channels to be filtered
- Impedance
- Currents (peak and nominal), voltages and permissible power factor
- Common mode/differential mode characteristic
- Leakage current
- Electric strength (Should be in accordance with IEC 60092-101)

(IEC 60533 1999: 37.)

Long signal wires may easily lead to induced interferences within the wires and distort the signal. Filters are one way to protect from these interferences. While choosing a filter for signal line the type of signal (analog/digital) and communication frequency should be considered as well as the loss in signal power. Other criteria to consider while choosing a filter include:

- Matching to the characteristic impedance of the cable, the signal source or the signal receiver
- Cross-talk of multi-channel filters
- Permissible capacity due to the wanted signal
- Permissible ripple in the pass-band
- Electric strength, pulse strength
- Permissible intermodulation distortion
- Environment compatibility.

(IEC 60533 1999: 38.)

Overvoltage protection should be implemented by applying surge arrestors, varistors and breakdown diodes to vulnerable devices. The critical criteria while choosing overvoltage protection components are to have adequate attenuation of overvoltage but retain un-distorted transmission for wanted signals. Other selection criteria include:

- Minimum insertion loss for wanted signals (in general < 1 dB)
- Maximum return loss (estimated value: a ≥ 20 dB)
- Sufficient peak power dissipation
- Minimum dissipation of intermodulation (for certain appliances in the high frequency range)

(IEC 60533 1999: 38, 39.)

4.2 Radio communication and navigation equipment (A)

Category A consists of all the radio and navigation equipment used on board a boat including the Global Maritime Distress Safety System (GMDSS). Also all their auxiliary equipment like antennas, power supplies and transfer lines are included. By using only equipment that meets the appropriate EMC standards can adequate EMC level be confidently reached with the measures described. (IEC 60533 1999: 39.)

Radio transmitters and receivers with low impedance antenna interface should be favored. A high impedance antenna interface should be placed so that the antenna cable inside deckhouse will be as short as feasible and the installation made so that capacitance is kept to minimum. Transmitting and receiving antennas should be properly decoupled from each other as well as from the boat's superstructure if it consists of conducting materials. Any conducting equipment within antennas' radiated zone should be appropriately grounded and non-metallic materials should be used in structural elements providing protective covering for the antennas. Special attention should be paid to screening if the receiving antenna's cables run in vicinity to transmitting antenna's cables. The recommended practices are to run the receiving antenna's cables in grounded cable tubes or to double screen the cables and ground the outer screen at penetration points of conducting surfaces. (IEC 60533 1999: 39.)

Power supply cables should be laid separately in one continuous length as far as practical. Screened signal and control cables should be used. When in proximity of transmitters and receivers the screens should also be grounded at conducting deck penetrations. Cable screens should always have continuous contact with equipment enclosures over the total circumference. (IEC 60533 1999: 40.)

Transformers should be isolated with a grounded internal screen winding (IEC 60533 1999: 39).

4.3 Power generation and conversion equipment (B)

Category B includes equipment used for AC power generation, conversion and periodic switching. These typically produce broadband interference and should be contained away from susceptible equipment like radio communication systems. (IEC 60533 1999: 40.)

As whole the electric supply network should have high short-circuit capacity which requires generators with lowest possible sub-transient reactance. The power supply should also be insulated from the boat’s structure. (IEC 60533 1999: 41.)

Designing properly working filter layout in tandem with converters is very demanding due to more static and dynamic frequency deviations in power generators compared to land based equivalents. If filters are used, they should be tuned to fifth and/or seventh harmonic and installed in parallel with converters. Resonance in system must be avoided with proper planning. With cycloconverter systems harmonics’ varying sidebands add another level of challenge to design. If the non-linear loads from converters seem to become a problem, a dedicated converter network suitably decoupled from main supply network may be used. (IEC 60533 1999: 41.)

Primary and secondary windings in transformers may be isolated with a metal screen to isolate interference from connected electronic equipment (IEC 60533 1999: 41).

If the power supply has a high content of harmonics, compensation capacitors for fluorescent lighting fixtures have to be equipped with inductance chokes to avoid overload. If electronic starters aren’t utilized in operation of fluorescent lighting fixtures, the lights should be connected in twin lamp configurations or with central compensation with an inductance choke for each group of lamps or without compensation. (IEC 60533 1999: 41.)

4.4 Equipment operated with pulsed power (C)

Radar, sonar and echo sounder systems operate by sending periodical high energy pulses that may easily affect devices with vulnerable low powered signal wires. On the other hand during receiving phase these category C equipment may become the susceptible party. (IEC 60533 1999: 41.)

The cables should have double screens or be placed within continuously grounded protective cable piping. To avoid interference during receiving phase, the cables should not be placed near other wires with high interference levels. The length of cables carrying the high powered pulses during transmission should be as short as possible and in no case run in vicinity of radio antenna cables. (IEC 60533 1999: 41.)

4.5 Switchgear and control systems (D)

Category D includes transient broadband interference producing equipment like switchboards, relays, magnetic valves, electric drives and oscillating or resonating combination of inductances and capacitances (IEC 60533 1999: 42).

The general practices are to implement voltage surge limiters close to corresponding inductances and high-frequency absorbing elements close to switching contacts. Proprietary DC and AC measures are as following.

For DC:

- suppressor diodes
- varistors
- RC combination
- Flyback diodes.

For AC

- varistors
- discharge paths with voltage-dependent resistor
- capacitors
- RC combination (resonance of RC combinations in conjunction with the inductivity of the circuit must be avoided)

(IEC 60533 1999: 42.)

4.6 Intercommunication and signal processing equipment (E)

Apart from intercom and signal processing equipment, category E also includes digital and analog transmission systems between sensors, displays, operator panels and computers. These devices communicate with low level signals making them susceptible to interference but are often equipped with switching power supplies making them also interference emitters. For emitted interference measures from categories B and D should also be considered. (IEC 60533 1999: 42.)

Maximum signal levels should be used for data transmissions traveling through long cables. Error correction or transmission signaling protocols might be required for proper operation when signal levels aren’t adequate. Where necessary, preamplifiers should be used at sensor locations. Minimal impedance within the system is desirable, especially for system inputs, to decrease capacitive coupling. To avoid asymmetrically induced low-frequency interference at low level signals, symmetric signal transmission should be used. For reference ground only single point connection should employed with easy access for inspections. In cases where this is not possible, optocouplers or transformers can achieve the necessary galvanic separation for the system components. (IEC 60533 1999: 42, 43.)

While considering instrument amplifiers, it should be taken into account that boats show asymmetrical or common-mode interference in levels of 1 V to 2 V and superimposed spikes of several hundred volts. The chosen amplifiers should be able to cope with these interference levels. (IEC 60533 1999: 43.)

A/D-converters should be of integrator type (IEC 60533 1999: 43).

Computers both emit and are susceptible to high-frequency interference and should be well screened if the computers' or other equipment's operation is disturbed by these interferences. (IEC 60533 1999: 43.)

4.7 Non-electrical items and equipment (F)

Conducting equipment may cause interference on board a boat if the contact points carry eddy currents. For example transmitting antennas can induce stray currents to metallic hull and superstructures within the boat. The interference is amplified by vibrations transmitted to the respective equipment and changes in conductivity between contact surfaces due to corrosion for example. (IEC 60533 1999: 44.)

Parasitic sources of broad-band interference to radio reception are for example:

- loose turnbuckles of the rigging
- loose wire ropes in railing stanchions
- insufficient lashing of containers
- loose derricks or other large items

Eddy currents in metallic structures below deck are caused by discharges from suppression capacitors, by transient effects in grounded networks and by using the boat's structure as the common return conductor for different circuits. These may lead to superimposed broadband interference in analog signals through reference potential variation. The possible causes are:

- pipe connections without ground connection
- loose metallic wall panels
- loose or isolated parts of cable trays or other equipment

Proper fixation of conducting items and use of low impedance ground connections helps prevent unnecessary interference. All items in proximity of transmitting antennas and exceeding 1 m in some dimension should be connected to boat's ground potential. The rig should either be grounded to boat’s structure or completely insulated from rest of the boat. Where detachable connections are used, good grounding should be ensured by bridging conductors over the connections. (IEC 60533 1999: 44, 45.)

4.8 Integrated systems (G)

Integrated systems comprise of the aforementioned equipment categories that are simultaneously operational and may produce interference from the combined operation of two or more systems. The problem may be amplified if portions of the system are in different parts of the boat affected by different kinds of interferences. (IEC 60533 1999: 45.)

In optimal situation the whole electrical system would be built in laboratory conditions and the correct operation of each device made sure in addition to measuring interference and susceptibility levels. Besides all the measures covered in categories A to F, all equipment and their capability to operate together should be documented for future reference with all the problems found and ways to correct them. (IEC 60533 1999: 45, 46.)

5 Full EMC analysis

A rough EMC analysis should be made based on the device information available from the manufacturer as well as installation locations and wiring routes. By doing this the possible interference inducing systems may be identified before a failure in expensive EMC tests.

All the data for each device should be recorded in EMI sheets for easy retrieval of needed information. Links to these sheets should be provided in the EMI matrix, which collects all the data together for analyzing. The following information should be gathered for successful EMC analysis:

- emission and immunity levels
- dimensions of equipment
- distances between the units
- data concerning power and signal cables

- data concerning the details of the installation
- levels in the electromagnetic environment
- electric and electronic data of the equipment, such as:
  - power
  - frequencies / frequency ranges
  - the sensitivity level of receivers
  - the transmitting power of transmitters

(IEC 60533 1999: 24, 25.)

This data should be available from the device's manufacturer and if some information is not available, an estimation may be used (IEC 60533 1999: 25). At this point the plans for cable routes and installation distances for devices should be known as well as EMC measures to be implemented.

Based on the data collected, a frequency survey is produced for the operating frequencies and their harmonic components. Two kinds of surveys can be made; one for conducted interference and other for radiated interference. Special attention should be paid to frequencies in which equipment's interference levels fall short of the required interference limits. This analysis is especially useful for transmitting and receiving equipment to see if same frequency range is used for both transmitting and receiving. An example of a frequency survey is shown in figure 10. (IEC 60533 1999: 25.)

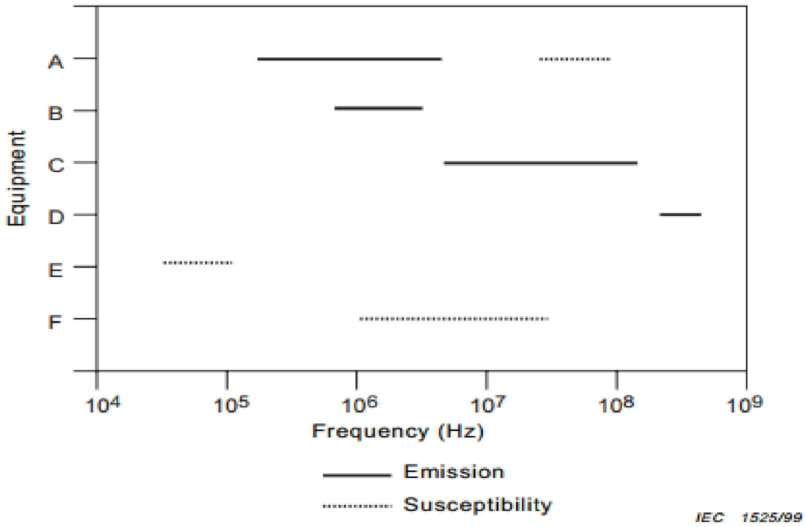


Figure 10. Frequency survey showing each equipment category's emission and susceptibility frequencies. (IEC 60533 1999: 28.)

In level survey equipment's emission and immunity levels are shown in frequency ranges. The interference limits should be also place in the survey to see how far the devices' levels are from these limits. A level survey for conducted interference will show directly where disturbances take place. For other types of coupling, calculations and tests have to be made to see if interference actually takes place. An example of level survey can be seen in figure 11. (IEC 60533 1999: 25.)

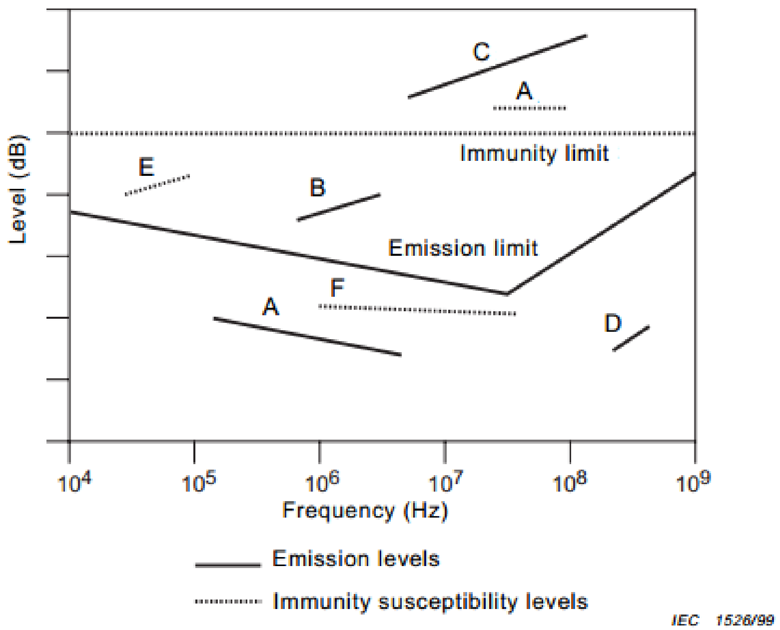


Figure 11. Level survey showing each equipment category's emission and immunity levels relative to allowed limits. (IEC 60533 1999: 28.)

The final part of analysis is EMI matrix which can be seen in appendix 2 table 1. In EMI matrix the devices are grouped based on the aforementioned categories from A to G with H added for devices in hazardous areas, and if the device is potentially emitter and/or susceptible to interference. The emitting devices are placed on the columns and susceptible devices are placed to rows. Same device may be placed in both column and row. At each crossing point the devices' level of compatibility is analyzed and tagged with a marker. The markers are shown in figure 12. (IEC 60533 1999: 24.)

Symbol	Meaning
–	No interference possible
+	Interference possible or present
⊕	Interference possible, but shown by analysis not to be present
#	Interference present or probable, according to analysis
# a(dB)	Interference present, and value according to analysis

Figure 12. The symbols and their meanings used in EMI matrix to show the interference level between two devices. (IEC 60533 1999: 29.)

Where EMI matrix shows interference taking place, calculations should be performed to see how bad the interference is. All the possible transmission routes, bandwidths and screening should be taken into account during the calculations. Due to many unforeseen variables and circumstances, the calculations will have a large margin of error which has to be considered when the results are examined. (IEC 60533 1999: 29.)

6 EMC testing a boat

It is advisable to EMC test the final assembly of the boat to make sure no harmful interference is radiated to other vehicles and electrical devices outside the boat as well as to the devices on board the boat. The standards depicting the process are CISPR 12 and CISPR 25 respectively. It should be noted that a boat is defined as notably smaller vessel in this part of the document compared to prior parts of the document. Boat means a vessel with maximum length of 15 m from here on instead of 24 m (CISPR 12 2009: 9). The tests are aimed for boats with internal combustion engine(s) and/or electric propulsion.

6.1 Measurements for off board device's safety

The measurements described are designed to guarantee disturbance free operation for broadcast receivers in residential area. The tests are performed in 30 MHz to 1 GHz frequency range at the distance of 10 m while the boat is either in outdoor test site (OTS) or inside an absorber lined shielded enclosure (ALSE). (CISPR 12 2009: 8.) The size of a boat sets demanding requirements for the test site as it needs to be very large and should have low levels of ambient interference for realistic measurement results.

6.1.1 Measurement equipment

The instrumentation used for EMC tests include, but are not limited to, spectrum analyzer, scanning receiver as well as both reference and broadband antennas. The equipment used should comply with the requirements in CISPR 16-1-1 standard. The measuring system should be able to have an accuracy of ±3 dB when measuring electric field strength and the deviation in frequency should be no more than ±1 % (CISPR 12 2009: 16).

6.1.2 Spectrum analyzer and scanning receiver parameters

The parameters used in spectrum analyzer and scanning receiver have to fulfil the requirements of CISPR 16-2-3. The recommended parameters for spectrum analyzer are shown in table 2 and for scanning receiver in table 3.

Table 2. Recommended parameters for spectrum analyzer.

Frequency range (MHz)	**Peak detector**		**Quasi-peak detector**		**Average detector**	
	RBW[a)]	**Scan time**	**BW[b)]**	**Scan time**	**RBW[a)]**	**Scan time**
30 to 1000	100 kHz / 120 kHz	100 ms / MHz	120 kHz	20 s / Mhz	100 kHz / 120 kHz	100 ms / MHz

[a)] Resolution bandwidth is defined at -3 dB.
[b)] Bandwidth is defined at -6 dB.

For peak measurements with spectrum analyzer, the video bandwidth should be at least three times the resolution bandwidth (RBW). (CISPR 12 2009: 15.)

Table 3. Recommended parameters for scanning receiver.

Frequency range (MHz)	**Peak detector**			**Quasi-peak detector**			**Average detector**		
	Band-width	**Step size[a)]**	**Dwell time**	**Band-width**	**Step size[a)]**	**Dwell time**	**Band-width**	**Step size[a)]**	**Dwell time**
30 to 1000	120 kHz	50 kHz	5 ms	120 kHz	50 kHz	1 s	120 kHz	50 kHz	5 ms
[a)] For purely broadband disturbance, the maximum frequency step size may be increased up to a value not greater than the bandwidth value.									

For both spectrum analyzer and scanning receiver, bandwidth has to be set so the noise floor is at least 6 dB lower than the limit curve. To achieve this 6 dB noise floor requirement, a preamplifier may be used between the measuring device and the antenna. (CISPR 12 2009: 15.)

6.1.3 Reference antenna

A balanced dipole antenna should be used as described in CISPR 16-1-14. Free space antenna factor should be used for reference antenna. For frequencies at 80 MHz or above, the antenna shall be resonant in length, and for frequencies below 80 MHz it shall be the length equal to the 80 MHz resonant length. The antenna should be connected to the feeder by a suitable symmetric-asymmetric transformer device. (CISPR 12 2009: 16.)

6.1.4 Broadband antennas

Any linearly polarized receiving antennas that can be normalized to the reference antenna for the 30 MHz to 1 GHz frequency range at the actual test site can be used. A broadband antenna shall be used when making measurements with an automated receiving system using a scanning measuring instrument. The requirements for broadband antennas are specified in CISPR 16-1-4. (CISPR 12 2009: 16.)

6.1.5 Open area test site

The base requirements used for boat testing site are derived from CISPR 16-1-4 intended for large automotive objects. The area used for testing should be free of any electromagnetically reflective objects and surfaces except for the boat, testing equipment and possible testing hut for a radius of 30 m from the center of test site. The testing instruments and hut may only be placed according to the grey area shown in figure 13. The distance between boat and the reference antenna should be 10,0 ± 0,2 m during the measurements while the boat is in water. If the test site requires to place the test equipment on water, they should be placed on non-metallic boat or test fixture placed with same distances as in land based measurement site. (CISPR 12 2009: 17.)

Due to outside ambient noise, a baseline ambient measurement is required. During this measurement the boat under test should not have any interference sources activated to get realistic ambient levels. The ambient measurement should be performed before and after the actual EMC test measurements. During both of the ambient measurements, the noise level should be at least 6 dB below the measurement limits shown in figure 17. For situations where the ambient noise levels surpass the test limits, CISPR 16-1-4 Clause 6 should be used as reference material to determine whether or not the measurements can be continued. (CISPR 12 2009: 18.)

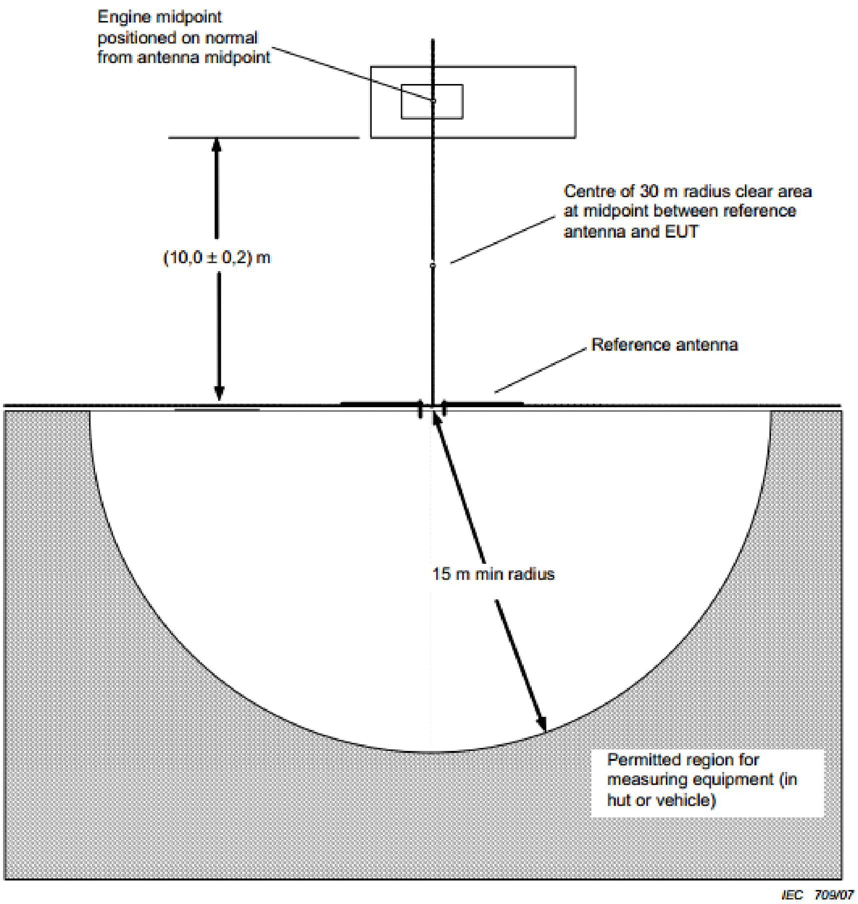
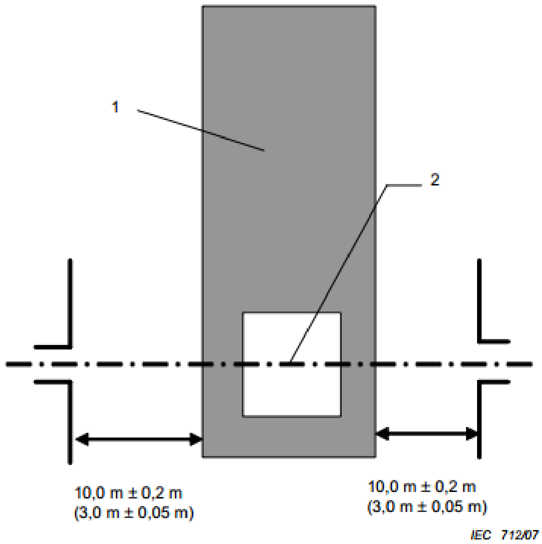


Figure 13. Placing of the test instrumentation and boat in outdoor testing site (OTS). (CISPR 12 2009: 18.)

6.1.6 Absorber lined shielded enclosure testing site

ALSE provides a controlled environment without changing weather conditions and better protection from ambient noise. As a down side, large enough ALSE for boat measurements are few and expensive to use. The measurements conducted in ALSE testing site should correlate with measurements from OTS, and the same 6 dB ambient noise difference to test limit levels applies. Inside an ALSE the noise level should be periodically measured or when test results indicate the possibility of non-compliance. (CISPR 12 2009: 19.)

All measurements should be made with the antenna polarized both horizontally (figure 14) and vertically (figure 15). The antenna's center should be placed horizontally 10,0 ± 0,2 m from the nearest metallic part of the boat and vertically 3,00 ± 0,05 m above the ground or water level. No electrical interaction between the antenna elements and support system nor transmission lines is allowed. One way to set the transmission line is to have it run straight behind the antenna element for 6 meters at the same height of the antenna's center of 3 m and then descend to ground level or below. The use of multiple antennas is also permitted but if the antennas are facing each other, one antenna should be set to horizontal polarization and the other to vertical polarization. (CISPR 12 2009: 20, 21.)



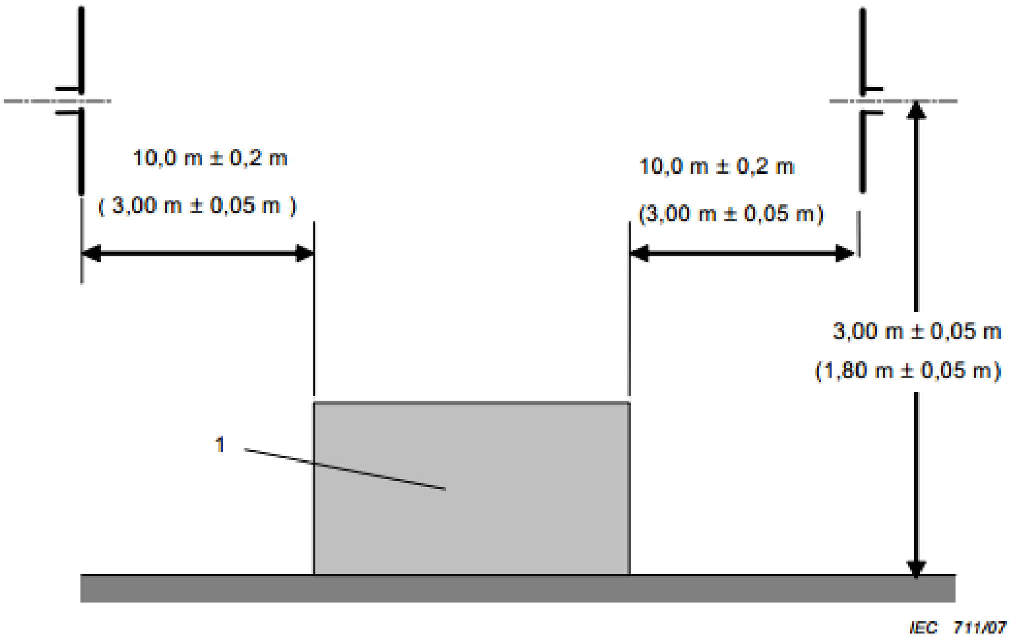
(Dimensions in brackets for 3 m antenna distance testing) Drawing not to scale

Key

1 Equipment under test

2 Engine midpoint positioned on normal from antenna midpoint

Figure 14. The horizontal placement of antennas inside an ALSE in respect of EUT and engine. (CISPR 12 2009: 21.)



(Dimensions in brackets for 3 m antenna distance testing) Drawing not to scale

Key

1 Equipment under test

Figure 15. The vertical placement of antennas in respect of the EUT. (CISPR 12 2009: 20.)

6.1.7 Test procedure

EMC tests are performed to both left and right side of the boat according to figures 14 and 15. Since moisture may affect the test results, it is advisable to test the boat in dry conditions or at least 10 minutes after precipitation has stopped falling. All the equipment automatically switched on with propulsion system are included in the measurements to achieve same results as in normal operation situation. If the boat is equipped with auxiliary engines, each should be measured separately if possible. Depending on the placement of the auxiliary engines, the boat may have to be positioned multiple times to achieve the required test positions for all engines according to figures 14 and 15. (CISPR 12 2009: 22.)

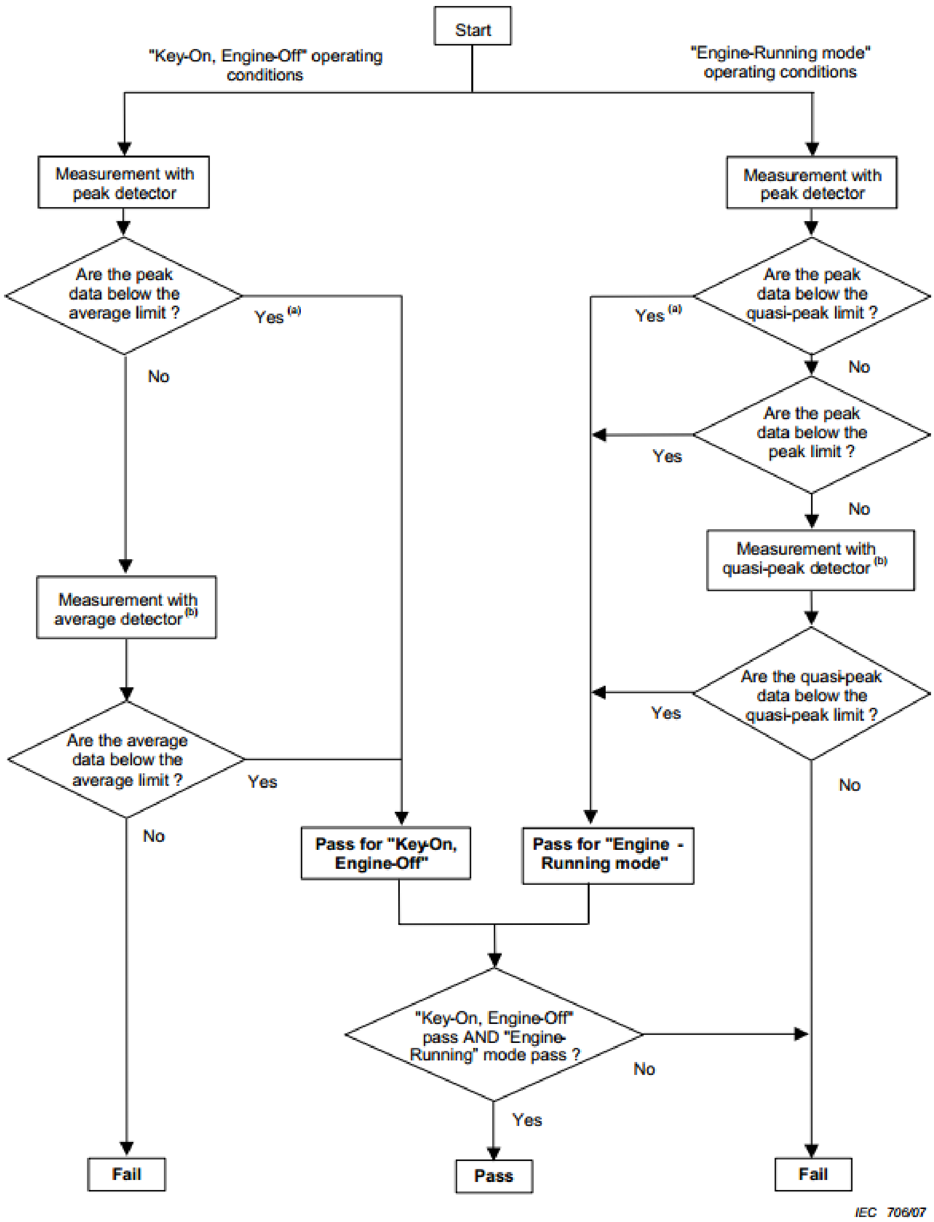
The first operation mode is “key on, engine off”, which means:

- The ignition switch is switched on.
- The engine is not operating
- The boat’s electronic systems are all in their normal operating mode.

The second operation mode is “engine running” mode. If the engine has 1 cylinder the engine speed during measurements should be (2500 ± 10 %) r/min and for engines with more cylinders the engine speed should be (1500 ± 10 %) r/min (CISPR 12 2009: 23).

During these measurements no person should be operating the boat. Instead a non-metallic mechanical arrangement may be used to keep the equipment in normal operation mode. (CISPR 12 2009: 23.)

It is possible to pass the tests with only peak detector measurements because peak detector will always show higher results than quasi-peak or average detector. If the measurement results with peak detector are below the average detector (figure 18) or quasi-peak detector limits (figure 17), the test is passed and no further measurements are required in the mode in question. If the peak detector results are higher than average or quasi-peak detector limits, then rest of the measurements should be performed according to figure 16. (CISPR 12 2009: 12.)



a Because measurement with peak detector is always higher than or equal to measurement with quasi-peak detector (and average detector respectively) and applicable peak limit is always higher than or equal to applicable quasi-peak limit (and average limit respectively), this single detector measurement can lead to a simplified and quicker conformance process.

b This flow-chart is applicable for each individual frequency, e.g only frequencies that are above the applicable limit need to be remeasured with quasi-peak detector (and average detector respectively).

Figure 16. Test procedure for measurements in accordance to CISPR 12. (CISPR 12 2009: 12.)

6.1.8 Test result requirements

The peak and quasi-peak limits for measurements conducted at 10 m antenna distance are shown in figure 17. For peak measurements either the 120 KHz or 1 MHz should be chosen as bandwidth used.

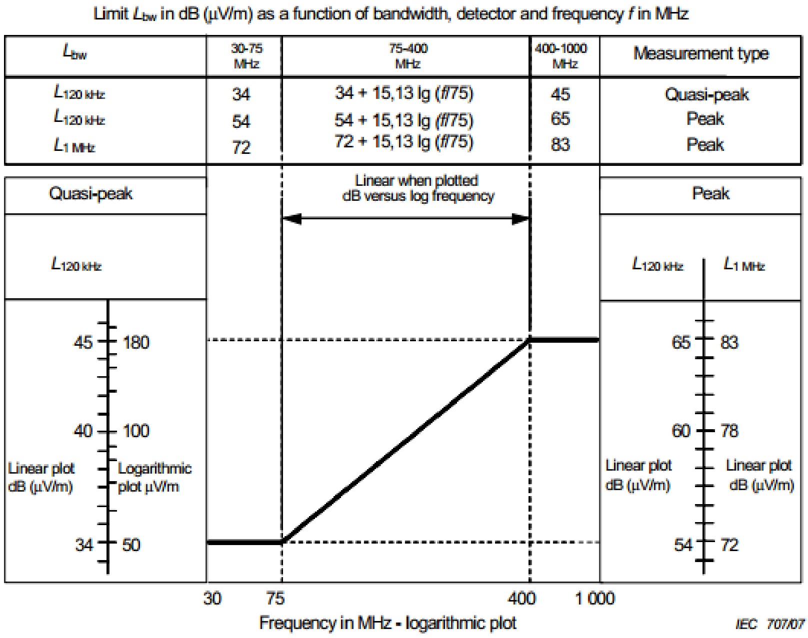


Figure 17. Test limits for peak and quasi-peak measurements. (CISPR 12 2009: 13.)

The average detector limits are shown in figure 18. It should be noted that if the boat has already passed the average emission requirements of CISPR 25 Clause 5, another average emission test is not necessary. (CISPR 12 2009: 13.)

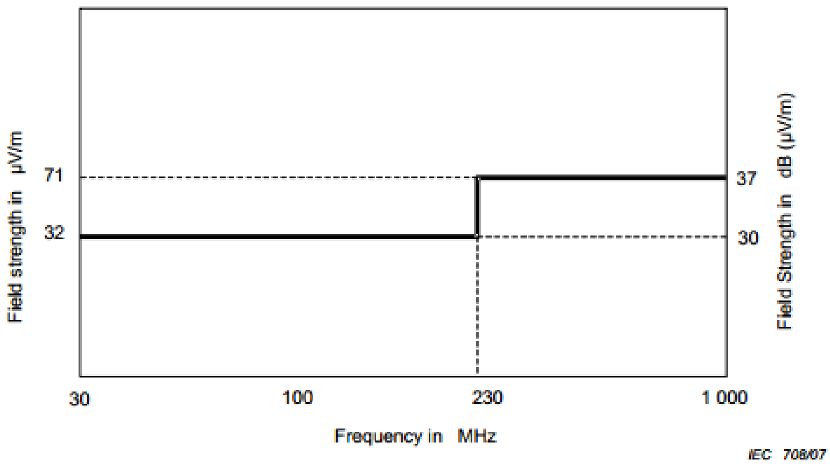
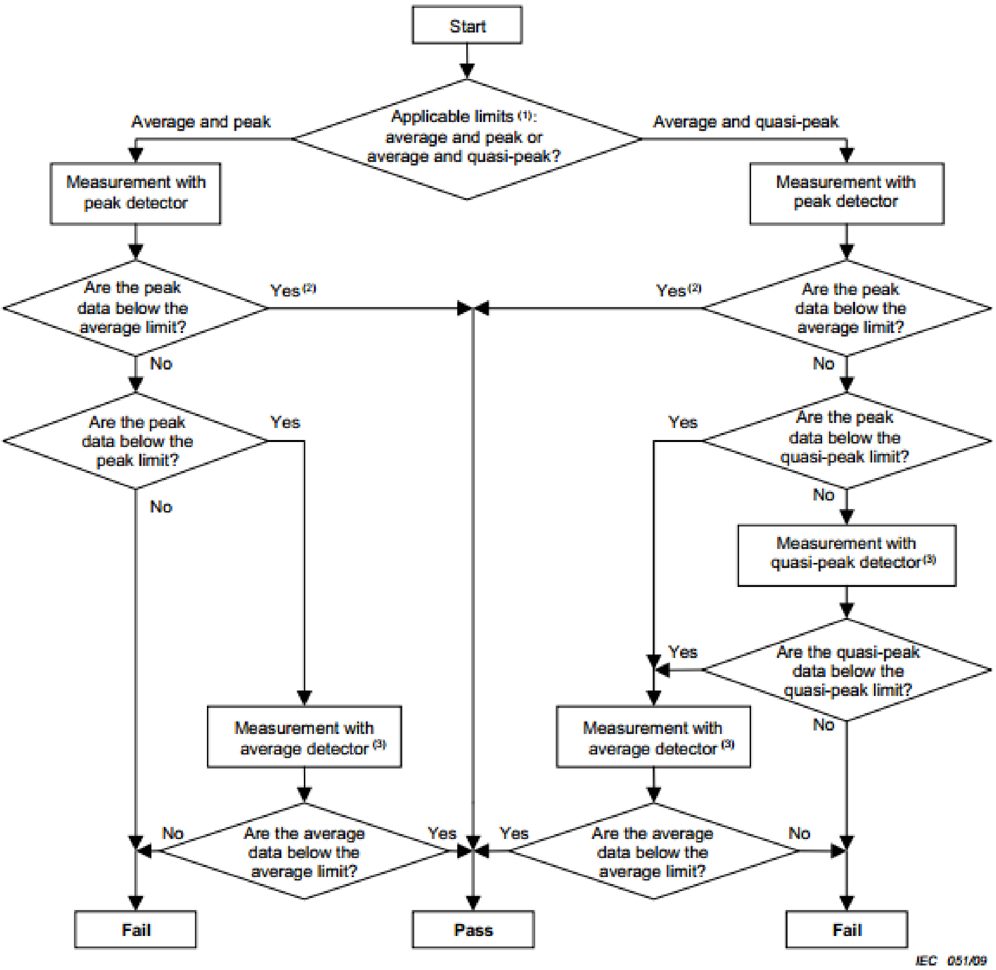


Figure 18. Test limits for average emission measurements. (CISPR 12 2009: 14.)

6.2 Measurements for on board receiver protection

Mainly the same methods as in *7.1 Measurements for the off board device's safety* apply. Clarifications are given for deviating parts. The measurements need to be made only in the frequency ranges where devices on board the boat are receiving (CISPR 25 2008: 9, 10). The order of measurements is shown in figure 19.



NOTE 1 The conformance should normally be obtained by compliance to both average and peak limits or both average and quasi-peak limits unless the test plan defines that conformance can be obtained by compliance to the single appropriate limit) *(depending on the case, peak, or average, or quasi-peak)*.

NOTE 2 Because measurement with peak detector is always higher or equal to measurement with average detector and applicable peak limit is always higher or equal to applicable average limit, this single detector measurement can lead to a simplified and quicker conformance process.

NOTE 3 This flow-chart is applicable for each individual frequency, e.g. only frequencies that are above the applicable limit need be remeasured with average or quasi-peak detector.

Figure 19. The test procedure for on board device's safety measurements. (CISPR 25 2008: 14.)

6.2.1 Power supply

A power supply should be used when necessary to achieve the set voltage limits. For 12 V nominal supply voltage system the voltage should be within 11 V to 14 V while ignition is on but engine is off. While the engine is running the voltage should be within 13 V to

16 V. For 24 V nominal supply voltage system the voltage should be within 22 V to 28 V when engine is off and within 26 V to 32 V when the engine is running. The vehicle battery may be connected in parallel with the power supply when specified in the test plan. (CISPR 25 2008: 18, 19.)

6.2.2 Antenna

The antenna type supplied with the device is to be used for measurements. If the vehicle/device is not supplied with an antenna, the following table 4 may be used as reference. The antenna type and location should be included in the test plan.

Table 4. The measurement antenna types for different frequency ranges when no antenna is supplied with the receiving device. (CISPR 25 2008: 20.)

Frequency (MHz)	**Antenna type**
0,15 to 6,2	1 m monopole
26 to 54	loaded quarter-wave monopole
68 to 1000	Quarter-wave monopole
1000 to 2500	As recommended by the vehicle manufacturer

6.2.3 Requirements for measurement instrumentation

The AM broadcast bandwidth measurements have been divided into three sections: long wave at 150 kHz to 300 kHz, medium wave at 530 kHz to 1.8 MHz and short wave at 5.9 MHz to 6.2 MHz. Output impedance of impedance matching equipment should be 50 Ω. The gain or attenuation of the measurement antenna system should be known within a ± 0.5 dB and it should remain within 6 dB margin during the measurements as shown in figure 20. A 1 dB compression point should occur at a sine wave voltage level greater than 60 dB. Compression point is the input signal level at which the gain of the measuring system becomes non-linear such that the indicated output deviates from an ideal linear receiving system's output by the specified increment in dB. The noise floor of the measuring system should be at least 6 dB below the applicable limit. The dynamic range is from noise floor up to the 1 dB compression point. The impedance at the input of the matching network should have a resistance of at least 100 kΩ in parallel with a maximum capacitance of 10 pF. (CISPR 25 2008: 19, 20.)

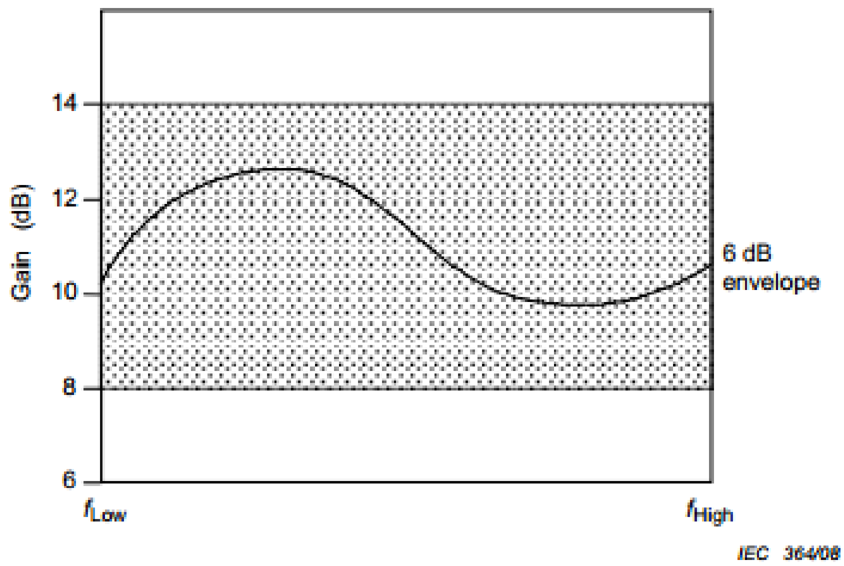


Figure 20. The 6 dB marginal in which the gain/attenuation should remain. (CISPR 25 2008: 20.)

For FM broadcast bandwidth of 76 MHz to 108 MHz measurements should be taken with a measuring instrument which has an input impedance of 50 Ω. If the standing wave ratio (SWR) is greater than 2:1 an input matching network should be used. Appropriate correction should be made for any attenuation/gain of the matching unit. (CISPR 25 2008: 20.)

The test procedure assumes a 50 Ω measuring instrument and a 50 Ω antenna in the frequency range of 26 MHz to 2,5 GHz. If a measuring instrument and an antenna with differing impedances are used, an appropriate network and correction factor should be used. (CISPR 25 2008: 20.)

Parameters to use with spectrum analyzer and scanning receiver at each frequency range for on board receiver safety measurements can be seen in appendix 3 tables 1 and 2 respectively.

6.2.4 Operating conditions

To take into account the different operating conditions of the EUT and their influence on the interference levels, a peripheral interface unit should be used to simulate the vehicle installation. All the significant connections normally going into the EUT should be connected to the peripheral interface unit. The EUT should be possible to control through the peripheral interface unit. The unit may be placed within the ALSE or outside of it with other measurement instrumentation. When placed within the ALSE the peripheral interface unit's disturbance levels should be at least 6 dB below the limits specified in the test plan. (CISPR 25 2008: 15.)

6.2.5 Test site

The measurements should be made within an absorber lined shielded enclosure that has enough space to accommodate the boat and still have at least 1 m of free space between the walls and boat as well as between antennas and the ceiling (CISPR 25 2008: 15,16).

6.2.6 Method of measurement

The interference level is measured from the antenna's coaxial cable at the receiver end. The signal is routed outside of the shielded enclosure through a bulkhead connector to measuring instruments. A decoupling network similar to that used in the radio should be used in case of an active antenna. During AM broadcast band measurements, the boat should be electrically isolated from ALSE's ground potential by means of an isolation transformer, sheath-current suppressor, battery-powered measurement instrumentation, fiber optics, etc. If the boat has multiple mounting positions for receiver, then all the locations should be tested according to test plan. (CISPR 25 2008: 20, 21.)

6.2.7 Required results

For the test limits the measured frequency band has been split to smaller frequency bands based on the typical operating frequencies of different devices used on board a boat. This makes it possible to not measure unused frequency bands and save time during the measurements. The test limits for each frequency band can be found in appendix 4 table 1.

7 Summary

The rapid development of electrical devices in the two last decades also affects the way boats need to be designed for present and future compatibility. The large amount of electronic equipment on board a boat has led to a need for electromagnetic compatibility requirements to make sure all the devices will operate as intended while multiple other devices are used nearby. Some marine and telecommunication organizations have taken up the task and provided a comprehensive collection of standards addressing the needs of EMC in boats. The standards include i.a. individual tests for single electrical devices, recommendations for installations and EMC test requirements for entire boat measurements.

The design of any boat’s electrical system should contain a good amount of consideration for electromagnetic compatibility. One of the most important parts for boat’s final EMC are the equipment installed in the boat. The manufacturer of the boat should have EMC test report for every electrical equipment to be installed in the boat. To increase the likelihood of the boat to be electromagnetically compatible when ready, all the individual equipment should fulfil the requirements of appropriate standard, in this case IEC 60945.

When the equipment have been chosen and a plan has been made for their mounting locations and wiring routes, the devices should be divided into groups based on their emission and susceptibility properties. After this a crude evaluation can be performed to see where electromagnetic interference may take place and the plans may be revised to take these probable interference locations into consideration. Usually the methods to mitigate the interference include better screening and larger spacing between devices or cables. The device groups also make it easier to determine the most effective methods to lessen interference.

Finally the electromagnetic compatibility of the whole boat is determined with EMC tests. The tests are meant to ensure the boat does not disturb electrical equipment outside the boat nor devices within the boat. An absorber lined shielded enclosure is recommended for these tests, but due to the large size of a boat, not many large enough test facilities are available. It is also possible to perform the tests unofficially with the help of an organization that has access to necessary test equipment. Universities and universities of applied sciences may have these equipment and the required know-how to perform the tests. The major factor for the success of unofficial tests culminates to having low enough ambient noise levels from the surrounding area. The tests should always be conducted according to the related standards with proper test plan and test report.

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Categories for different equipment cabling

Table 1. Categories for different equipment cabling. (IEC 60533 1999:36.)

Cables for	Level	Emission/ Immunity rating	Cable category	Cable type[4)]	Applicable standard
Radio receiver signals[2)] TV receiver signals Video Signals	0,1 mV to 500 mV	Extremely sensitive	3	Coaxial	IEC 60096-1
Analogue and digital signals Telephone signals Loudspeaker signals Control signals Alarm signals	0,1 V to 115 V	Sensitive	2	Twisted Single screened Screened twisted pairs	IEC 60092-374 IEC 60092-375 IEC 60092-376
Power supply[1)] Lighting	10 V to 1000 V	Potentially disturbing	1	Below deck: non screened Above deck: twisted, screened	IEC 60092-350 IEC 60092-353
High-power transmission signals Pulsed high-power signals[2)]	10 V to 1000 V	Extremely disturbing	4	Coaxial Screened power	Special cable
High powered semi-conductor converter				Twisted Screened	IEC 60092-350 IEC 60092-353
Special applications		Special	5		
Fiber optics			-		

1) Equipment and auxiliary equipment for radio communication and radio navigation should be fitted with screened power supply cables.
2) Receiving antenna cables should be installed with double screen cables or coaxial cables inside protective piping
3) Cables for radar, sonar equipment and echo sounders should be double screen cables or coaxial cables inside protective piping.
4) The "filling factor" for cable screens as required by the IEC should be adhered to and the transfer impedance at 10 MHz as determined by IEC 60096-1 should not exceed 30 mΩ/m.

EMI matrix

Table 1. The EMI matrix showing emitting devices in columns and susceptible devices in rows. (IEC 60533 1999: 27.)

	Equipment and installation categories	Examples of equipment	Type of signal	Susceptible device	Emitters				
					B1	B2	G2	H1	H2
A	Radio communication Radio navigation	GMDSS equipment receivers	Extremely sensitive	A1					
		-transmitters	Extremely jamming	A2					
		Gyro-compass	Sensitive	A3					
		Steering system /autopilot	Sensitive	A4					
		Integrated wireless communication systems	Sensitive	A5					
B	Power generation and conversion	Electric machinery	Non-sensitive	B1					
		Electronic exciters	Jamming	B2					
		Converters	Jamming	B3					
		Transformers	Non-sensitive	B4					
		Lighting armatures	Non-sensitive	B5					
C	Equipment operating with pulsed power	Radar	Jamming	C1					
		Sonar	Jamming	C2					
		Doppler log	Jamming	C3					
		Echo sounder	Jamming	C4					
D	Switchgear and control systems	Circuit breakers / contactors	Non-sensitive	D1					
		Electronic control devices	Sensitive	D2					
		Relay operated control devices	Sensitive	D3					
		Electronic protection equipment	Sensitive	D4					
E	Intercommunication and signal processing equipment	Electronic alarm monitor	Sensitive	E1					
		Electronic control system	Sensitive	E2					
		Automation system	Sensitive	E3					
		Computers, sensors	Sensitive	E4					
F	Non-electrical items + equipment	Rigging	Non-sensitive	F1					
G	Integrated systems	Integrated navigation system (INS)	Sensitive	G1					
		Integrated bridge system (IBS)	Sensitive	G2					
H	Equipment in hazardous areas	Explosion proof equipment	Non-sensitive	H1					
		Certified intrinsically safe equipment	Non-sensitive	H2					

CISPR 25 spectrum analyzer and scanning receiver parameters

Table 1. Parameters to use with spectrum analyzer at each frequency range. (CISPR 25 2008: 17.)

Service / Frequency range (MHz)		Peak detection		Quasi-peak detection		Average detection	
		RBW at -3 dB	**Scan time**	**RBW at -6 dB**	**Scan time**	**RBW at -3 dB**	**Scan time**
AM broadcast and mobile services	0,15 - 30	9/10 kHz	10 s / MHz	9 kHz	200 s / MHz	9/10 kHz	10s / MHz
FM broadcast	76 - 108	100/120 kHz	100 ms / MHz	120 kHz	20 s / MHz	100/120 kHz	100 ms / MHz
Mobile services	30 - 1000						
TV Band I TV Band II TV Band III	41 - 88 174 - 230 470 - 890						
DAB	171 - 245						
DTTV	470 - 770	100/120 kHz	100 ms / MHz	Does not apply	Does not apply	100/120 kHz	100 ms / MHz
Mobile services	1000 - 2500	100/120 kHz	100 ms / MHz	Does not apply	Does not apply	100/120 kHz	100 ms / MHz
GPS L1 civil	1567 - 1583	Does not apply	Does not apply	Does not apply	Does not apply	9/10 kHz	1 s / MHz

Table 2. Parameters for scanning receiver at each frequency range. (CISPR 25 2008: 18.)

<table>
<tr><th colspan="2">Service / Frequency range (MHz)</th><th colspan="3">Peak detection</th><th colspan="3">Quasi-peak detection</th><th colspan="3">Average detection</th></tr>
<tr><th></th><th></th><th>BW at -6 dB</th><th>Step size</th><th>Dwell time</th><th>BW at -6 dB</th><th>Step size</th><th>Dwell time</th><th>BW at -6 dB</th><th>Step size</th><th>Dwell time</th></tr>
<tr><td>AM broadcast and mobile services</td><td>0,15 - 30</td><td>9 kHz</td><td>5 kHz</td><td>50 ms</td><td>9 kHz</td><td>5 kHz</td><td>1 s</td><td>9 kHz</td><td>5 kHz</td><td>50 ms</td></tr>
<tr><td>FM broadcast</td><td>76 - 108</td><td rowspan="4">120 kHz</td><td rowspan="4">50 kHz</td><td rowspan="4">5 ms</td><td rowspan="4">120 kHz</td><td rowspan="4">50 kHz</td><td rowspan="4">1 s</td><td rowspan="4">120 kHz</td><td rowspan="4">50 kHz</td><td rowspan="4">5 ms</td></tr>
<tr><td>Mobile services</td><td>30 - 1000</td></tr>
<tr><td>TV Band I
TV Band II
TV Band III</td><td>41 -88
174 - 230
470 - 890</td></tr>
<tr><td>DAB</td><td>171 - 245</td></tr>
<tr><td>DTTV</td><td>470 - 770</td><td>120 kHz</td><td>50 kHz</td><td>5 ms</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>120 kHz</td><td>50 kHz</td><td>5 ms</td></tr>
<tr><td>Mobile services</td><td>1000 - 2500</td><td>120 kHz</td><td>50 kHz</td><td>5 ms</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>120 kHz</td><td>50 kHz</td><td>5 ms</td></tr>
<tr><td>GPS L1 civil</td><td>1567 - 1583</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>Does not apply</td><td>9 kHz</td><td>5 kHz</td><td>5 ms</td></tr>
</table>

CISPR 25 required results

Table 1. The test result limits for different frequency ranges and testing methods. (CISPR 25 2008: 23.)

Service / Band	Frequency (MHz)	Terminal disturbance voltage at receiver antenna terminal in dB (μV)		
		Peak	Quasi-peak	Average
BROADCAST				
LW	0,15-0,30	26	13	6
MW	0,53-1,8	20	7	0
SW	5,9-6,2	20	7	0
FM	76-108	26	13	6
TV Band I	41-88	16	-	6
TV Band III	174-230	16	-	6
DAB III	171-245	10	-	0
TV Band IV/V	468-944	16	-	6
DTTV	470-770	20	-	10
DAB L band	1447-1494	10	-	0
SDARS	2320-2345	16	-	6
MOBILE SERVICES				
CB	26-28	20	7	0
VHF	30-54	20	7	0
VHF	68-87	20	7	0
VHF	142-175	20	7	0
Analogue UHF	380-512	20	7	0
RKE	300-330	20	-	6
RKE	420-450	20	-	6
Analogue UHF	820-960	20	7	0
GSM 800	860-895	26	-	6
EGSM/GSM 900	925-960	26	-	6
GPS L1 civil	1567-1583	-	-	0
GSM 1800 (PCN)	1803-1882	26	-	6
GSM 1900	1850-1990	26	-	6
3G / IMT 2000	1900-1992	26	-	6
3G / IMT 2000	2010-2025	26	-	6
3G / IMT 2000	2108-2172	26	-	6
Bluetooth/802.11	2400-2500	26	-	6