EM emissions test platform implementation for satellite electric propulsion systems and electronic subsystems

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EM emissions test platform implementation for satellite electric propulsion systems and electronic subsystems

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ABSTRACT

Modern gridded ion thrusters for CubeSats operate by generating high power and can pose challenging problems with Electromagnetic Interference (EMI). In order to verify compatibility with neighbouring equipment, strict standards such as the military standard MIL-STD-461G, are required to be followed to achieve Electromagnetic Compatibility (EMC). To avoid abrupt and cataclysmic delays in production time, in case the product fails to comply with the requirements, companies integrate in-house pre-compliance tests into their development phase. The objective is to implement in-house measurement methods on an electric propulsion model NPT30 developed by ThrustMe. This document explains the process and methods to perform conducted emission test on power lines and radiated emission tests in the magnetic field. A custom measurement system integrity verification was developed for the radiated emission test. The presented results provide the engineers at ThrustMe an insight on the electromagnetic behaviour on the ion thruster NPT30 and whether modifications need to be included in the next development iteration to mitigate for the detected excessive emission levels. When EMC methods are implemented early on in the development process, there are more pre-emptive mitigation options with less costs in time and money. By performing in-house pre-compliance tests and taking measures to prepare for the tests at a certified EMC test house, the company can be more confident in their product at passing the EMC tests. Based on the two performed in-house tests, the engineers at ThrustMe began to include mitigation methods in the following circuit design iterations.
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<td>CAN</td>
<td>Controller Area Network</td>
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<td>CE</td>
<td>Conformité Européenne (French for European Conformity)</td>
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<td>CISPR</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>DoD</td>
<td>Department of Defence</td>
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<td>EMC</td>
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<td>GUI</td>
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<td>Power Processing Unit</td>
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<td>RF</td>
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Chapter 1

INTRODUCTION

The Master’s Thesis is centered around the implementation of in-house pre-compliance test methods on electromagnetic emission measurements based on the military standard MIL-STD-461G. The conducted emission CE102 and radiated emission RE101 tests are performed on the electric propulsion system NPT30, developed by ThrustMe.

The following document is structured in the presented manner:

- Chapter 1: introduction to the requirements of EMC standards and the importance of including its awareness in the development phase.
- Chapter 2: literature overview on the need for EMC standardisation and the nature of the measurement procedures for spacecrafts, including required equipment. The chapter introduces the ion thruster - subject to the following tests.
- Chapter 3: approach on the setup based on the military standard MIL-STD-461G for tests CE102 and RE101 and verifying the measurement system integrity.
- Chapter 4: measurement results obtained from the conducted and radiated emission tests.
- Chapter 5: conclusion about the performance and execution of the in-house measurements and reflection on the master’s thesis.
- Chapter 6: discussion on future work that involves improvements in measurement equipment and workflow.
- Appendix A: Octave code for creating presentable data plots according to the standard specifications.
- Appendix B: Derivation of the Ampere’s law to find the magnetic field strength at a distance from the center of the coil.
1.1 Motivation

The effects from Electromagnetic Interference (EMI) can be considered destructive to vital electrical subsystems regarding space missions. Verifying that spaceflight systems are electromagnetically compatible is one of the necessary precautions to ensure a successful mission. In an ongoing stream of technological advancements in developing more autonomous, sensitive and small-scale electrical solutions, Electromagnetic Compatibility (EMC) has an important future involvement regarding spacecrafts and their payloads. By designing the electrical systems to be electromagnetically compatible with the entire spacecraft, no hazardous EMI from on-board equipment can be expected (Bogorad et al., 2011). Once the spacecraft experiences disturbances from hazardous EMI, the success of the mission depends on whether this has been anticipated and is therefore equipped with methods for mitigation in case of spacecraft charging (Lai, 2003).

According to the definition by International Electrotechnical Commission (IEC), EMC describes the capability of an electronic and electrical system or components to function correctly in its electromagnetic environment i.e. is not susceptible to disturbances nor interferes with the operation with surrounding equipment. The electromagnetic environment translates to the sum of all signals, either caused intentionally or unintentionally by the surrounding internal or external devices and may cause EMI problems via radiation or conduction emissions (J. J. Goedbloed, 1992).

1.2 Problem statement

The cost of time and money increases as the device is tested for EMC in the later stage of the development process. It is expected for the company developing a device to ensure electromagnetic compatibility through optional pre-compliance measurements done in-house or at official facilities, followed by the compulsory EMC tests earning the final product the appropriate certification.

The main issues with failure to comply with the standards are the following long delays in the redesign process and rise in costs in the financial budget i.e. additional test lab visits along with engineering costs, see illustration 1.1. A visit to the test house, depending on the procedures, can be estimated to take from few days to over a week and the test report would arrive in another few days (Teschler, 2018). Therefore, from a business point of view, it is wise to incorporate pre-compliance into the product development process to keep visits to the test house
to the bare minimum. The benefits include identifying potential issues early and assessing immediate feedback on the impact of design changes. It is possible to conduct simulations to estimate the performance but it does not replace the actual measurements. With in-house measurements, the engineers can perform tests on their own schedule, achieve an intricate understanding of the behaviour of the device and increase confidence in compatibility before scheduling for the test house (Bogorad et al., 2011).

![Available EMC measures for mitigating EMI with the costs per EMC measure throughout the various stages of product development. Redrawn from J. Goedbloed, 1987.](image)

**Figure 1.1:** Available EMC measures for mitigating EMI with the costs per EMC measure throughout the various stages of product development. Redrawn from J. Goedbloed, 1987.

This thesis focuses on in-house pre-compliance measurements on radiated and conducted emissions and takes advantage of the benefits of early planning for EMC such as detecting errors early, low test and design costs, and lower risk of failure leading to assured compliance. In addition, the engineers gain a better understanding of the electromagnetic characteristics of the device and perform time-efficient troubleshooting. The nature of the work procedure of this thesis, such as preparing the test bench and data analysis, allowed to operate in parallel with the product’s development process. The product is constantly going through its own set of experiments and would be taken out of the line for EMC tests for only a few hours.

It is important to state that in case the pre-compliance tests prove a pass with in-house measurements, the certified compliance tests cannot be avoided as the product under test requires an EMC label by the appropriate organisation.
1.3 Objectives

The goal is to perform electromagnetic compatibility testing methods with in-house measurements. The used methods follow the specified military standards and will give an estimation of whether the device passes or fails the tests. Based on the frequency of the peaks, the culprits of the electrical system can be identified and relevant mitigation measures can be taken into account at the design stage. The more early on in the development phase the EMI mitigations are carried out, the wider range of methods the engineers have.

[EMC] is not required only to comply with standards but is applicable for system integration as based on the measured results. The placement planning on the spacecraft in reference to the neighbouring instruments and equipment is based on aforementioned test reports, to ensure nominal operations between submodules. Hence, for the thruster, which is the subject of the tests, besides verifying electromagnetic compatibility according to the standards, it is important to provide information for the client to determine compatibility between the modules.

1.4 Outline

A case study about electromagnetic compatibility of an electric propulsion model is performed to develop in-house pre-compatibility measurement methods based on the military standard MIL-STD-461G. The ion thruster is tested for conducted emission levels on power lines and radiated emissions in near-field. By providing data through reliable in-house [EMC] tests, the engineers at ThrustMe can include mitigation methods in the early stages of the product’s development process. Besides, based on the obtained results, the customers of ThrustMe can conduct susceptibility tests to assure reconcilable operations (Mallette and Adams, 2011). Ensuring the absence of [EMI] contributes to the success of space flight programs.
Electromagnetic Compatibility (EMC) is a condition that prevails when various electrical devices are performing their functions accordingly to intended design in its common electromagnetic environment. Electromagnetic Interference (EMI) is electromagnetic energy that disturbs, interrupts, obscures or degrades the effective performance of the electrical equipment. EMC standards establish verification requirements to control the characteristics of EMI emission and susceptibility levels on electrical and electromechanical equipment and its subsystems.

2.1 Standards in EMC

The application of establishing regulations for EMC started at the beginning of the 20th century when the Federal Communications Commission (FCC) was founded as an independent agency of the United States Government. Initially, different frequency bands were issued for preventing radio frequency interference between different users. Failure prevention methods due to radiating emissions were devised for private radio stations and military equipment such as radar systems, aircraft and its electrical subsystems.

Furthermore, more attention was being paid to different techniques for grounding, filtering and shielding making electromagnetic compatibility an engineering branch next to antenna design and communication technology. This growth lead to the development of new types of emission and immunity standard-setting organisations such as International Special Committee on Radio Interference (CISPR), IEC, International Organization for Standardization (ISO), Society of Automotive Engineers (SAE) and European Standards (EN) (JoAnne Yates, 2019). As of now the largest association of technical professionals is the Institute of Electrical and Electronics Engineers (IEEE) which was formed when the American Institute of Electrical Engineers (AIEE) and the Institute of Radio Engineers (IRE) merged in 1963.

However, the first Radio Frequency Interference (RFI) standards were published at the end of World War II in 1945 titled JAN-I-225 "Radio Interference Measurement". It featured interference measurements in the frequency range between 150 kHz and 20 MHz. In the subsequent years, the standards were updated and new versions were
continuously issued based on published recommendations which began including a
wider range of frequencies for different electrical equipment and digital systems as
they became more available to the general public.

Generally, **EMC** standards provide fundamental conditions and limits on how the
product must perform, all while specifying test procedures depending on the device’s
product family and general use with consideration to its environment when in
operation. **EMC** standards can be commonly divided along the following industries:
commercial, automotive, aerospace, medical and military.

One EMC standard that might be the most familiar to a consumer in Europe is
the **Conformité Européenne** (French for European Conformity) (**CE**) icon depicted
in figure 2.1 which is labeled onto electrical devices. The CE Mark ensures that
products sold in the European Union meet the required directives to safeguard health,
safety and environmental protection, including electromagnetic compatibility.

![CE Mark](image)

**Figure 2.1:** The CE Mark indicating conformity with health, safety and environmental
protection standards for products sold in the European Economic Area (EEA).

Spacecraft equipment is considered by National Aeronautics and Space Administra-
tion (NASA) to fall under the military industry (GSFC-STD-7000A, 2013) (MIL-
STD-461G, 2015). The European Space Agency (ESA) provides their standards for
product assurance in EMC in space projects and applications (ECSS-E-ST-20-07C,
2012), yet both space agencies address guidelines for grounding, shielding, bonding,
in-orbit Radio Frequency (RF) environments, and launch sites with varying limit
levels. Depending on the objectives of the spacecraft, the documents are used as
guides and in most cases, requirements are expected to be tailored to account for the
spacecraft’s special conditions (Mallette and Adams, 2011).

The type of **EMC** tests are emission and susceptibility with each type having two
subgroups in radiated and conducted. Therefore the tests are divided into four test
categories: Radiated Emissions, Conducted Emissions, Radiated Susceptibility and
Conducted Susceptibility. In some cases, susceptibility test limits are based on
measured emission levels from the device itself or external equipment, see figure 2.2.

![Diagram of EMC categories]

Figure 2.2: Relation between the EMC terms. Redrawn from J. Goedbloed, 1987.

Each of these categories has various tests and limits which cover certain frequency bandwidths and still have varying limits depending on the supply voltage, measured field type and intended industry (space, naval, military, etc). The requirements give the product developer defined limits that are measured with specified equipment, some of which are current and voltage sensors, Vector Network Analyser (VNA), Line Impedance Stabilisation Network (LISN), standardised antennas, and 50Ω impedance cables.

2.2 Failures and Anomalies from Electromagnetic Interference

When a spacecraft experiences anomalies, it is important to distinguish whether it occurred due to a command transmitted from the Ground Station or by interference on the spacecraft. The anomalies from the environment can be caused by radiation and the RF environment. There are multiple cases of operational failures or malfunctions on spacecrafts. Be it EMI coming from spacecraft charging from the natural space plasma (Bedingfield, Richard D Leach, Alexander, et al., 1996) or electromagnetic energy transferring from one device to another (R. Leach and Alexander, 1995).

For example, a Spinal Changes in Microgravity (SCM) experiment, as part of the International Microgravity Laboratory (IML-2) mission, flew on a Space Shuttle program mission called STS-65 in 1994. The SCM personnel detected an Alternat-
The current (AC) interference issue while testing on the ground. The EMC tests concluded that a portable fluorescent light was causing excessive radiated emissions. Therefore, payload operating procedures were modified to surpass the potential EMI problem.

To ensure that such phenomena do not pose malfunctions in the spacecraft, emission tests can be performed and include necessary mitigation methods in the development phase. Mitigation method examples commonly involve better shielding and grounding methods, and placement planning when integrating the spacecraft.

### 2.3 Power Transfer

The maximum power transfer theorem states that maximum power from a power source with a finite internal resistance is achieved when the load (Experiment Under Test (EUT)) resistance is equal to the source resistance viewed from its output terminals. For maximum power transfer the load impedance must be equal to the complex conjugate of the source impedance. This means that the two impedances have equal resistance, and also equal reactance in magnitude but opposite in signs. Energy is transferred from a power source to an electrical load by means of conductive coupling which is either resistive or hard-wire. By matching impedances to equivalent values, electric signal reflections and resulting noise from the load are minimized.

In the following figure 2.3, power is being transferred from the resistive source $R_{SOURCE}$ to a load with resistance $R_{LOAD}$. Efficiency $\eta$ is defined as the ratio of power between source and load voltage $V_{SOURCE}$ and $V_{LOAD}$. The following equation for power transfer efficiency is based on a basic voltage divider concept:

![Figure 2.3: Source and load circuit impedance](image-url)
\[ \eta = \frac{V_{\text{SOURCE}}}{V_{\text{LOAD}}} = \frac{R_{\text{LOAD}}}{R_{\text{LOAD}} + R_{\text{SOURCE}}} = \frac{1}{1 + \frac{R_{\text{LOAD}}}{R_{\text{SOURCE}}}} \] (2.1)

- If \( R_{\text{LOAD}} = R_{\text{SOURCE}} \), then \( \eta = 0.5 \)
- If \( R_{\text{LOAD}} \to \infty \) or \( R_{\text{SOURCE}} = 0 \), then \( \eta = 1 \)
- If \( R_{\text{LOAD}} = 0 \), then \( \eta = 0 \).

If the load impedance is made larger than source impedance, the efficiency is higher as a higher percentage of the source power is transferred to the load yet the magnitude of the load is lower due to increasing resistance of the total circuit.

### 2.4 Experiment Under Test - the Ion Thruster

ThrustMe was founded in 2017 in France and today consists of a team of around 15-20 people. The company focuses on developing space propulsion systems for mobility on satellites.

The experiment subject to electromagnetic compatibility tests is a stand-alone propulsion system called NPT30, designed and developed by ThrustMe. The thruster, illustrated in figure 2.4 is intended to provide orbital maneuverability for CubeSats and can be stacked for bigger platforms (Expo, 2019). The unit is a fully integrated up to 2U sized propulsion system that is based on a classical gridded ion thruster technology (Katz, 2008), comprised of a thruster, a Power Processing Unit (PPU), a propellant storage tank, a feed system and passive thermal management. The thrust is generated by accelerating ions across a set of biased grids, creating an ion beam which is charged and current neutralised by an external thermionic cathode. The system’s input voltage can be set between 12 V and 24 V and the bus interface can be either Controller Area Network (CAN) or I²C.
Figure 2.4: NPT30 Propulsion System by ThrustMe.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>0.4 – 1.1 mN</td>
</tr>
<tr>
<td>Total impulse</td>
<td>3000 N s*</td>
</tr>
<tr>
<td>Footprint</td>
<td>1.5 – 2 U</td>
</tr>
<tr>
<td>Total wet mass</td>
<td>1.3 – 1.7 kg</td>
</tr>
<tr>
<td>Total power</td>
<td>30 – 60 W</td>
</tr>
</tbody>
</table>

Table 2.1: Performance specifications of the NPT30 propulsion module.

*for baseline propellant quantity

When performing EMC tests, the ion thruster is measured in various operational modes: Standby, Plasma Flow Maintenance, Plasma Neutralisation System, Plasma Acceleration, and Operational State.

In the case of this thesis, the choice of which standard the product under test must follow depends on ThrustMe clients’ requirements which is likely based on their selected launcher, launch site, and neighbouring equipment e.g. whether it is intended to be integrated on-board another spacecraft, such as the International Space Station (ISS). The NPT30 model was requested by their client to prove electromagnetic compatibility based on the military standard (MIL-STD-461G, 2015). As ThrustMe is a European based company within the space industry, it is expected as well to apply to the series of European Cooperation for Space
Standardization (ECSS) Standards for product assurance, including electromagnetic compatibility. The following in-house measurements are done based on the military standard requirements, as demands from ThrustMe’s client had higher priority. Parallels with the ECSS Standards are discussed.

2.5 Military standard MIL-STD-461G: Electromagnetic compatibility

The military standard is a defence standard issued by the United States to ensure compatibility, commonality, reliability and interoperability on defence-related equipment, including space applications. It is common that the military standards are used by non-defense organisations and industries as it is known, compared to all other standards for commercial products, to pose the strictest limits, therefore if the tests pass the aforementioned requirements, the EUT is compatible for other requirements. The military standard, also called "MIL-STD", has set an inclusive set of engineering standards (Defence Washington DC., 1993) on communication, shock tests, symbology, environmental effects, pyrotechnics, etc. which are all categorised into five types of defense standards: interface, design criteria, manufacturing process, practices, and test methods. EMC is a safety critical requirement. A standard example of detrimental consequences due to EMI is causing an unwanted ignition of pyrotechnics.

The military standard MIL-STD-461G is the most recent (2015) issued standard out of the 461 series which sets the requirements for the control of EMI characteristics of subsystems and equipment. The military standard is constructed to establish verification requirements to characterise EMI emission and susceptibility on electrical equipment which is designed for the use by activities or agencies by the Department of Defence (DoD). Equipment from the following platforms or installations are applicable: surface ships, submarines, defence aircraft (army, navy, air force), space systems and launch vehicles, and ground control equipment (army, navy, air force).

The military standard has a total of 19 requirements involving emission and susceptibility, out of which not all apply to the whole experiment. In the requirement list shown in 2.5 it can be seen that some of them are meant for only testing power leads or antenna terminals while some measure the overall electromagnetic field emitted from the device. The scope of the thesis conducts tests based on requirements CE102 and RE101. It is emphasized that the aforementioned standard concerns the overall EMC performance of the subsystem once it is fully assembled.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE101</td>
<td>Conducted Emissions, Audio Frequency Currents, Power Leads</td>
</tr>
<tr>
<td>CE102</td>
<td>Conducted Emissions, Radio Frequency Potentials, Power Leads</td>
</tr>
<tr>
<td>CE106</td>
<td>Conducted Emissions, Antenna Port</td>
</tr>
<tr>
<td>CS101</td>
<td>Conducted Susceptibility, Power Leads</td>
</tr>
<tr>
<td>CS103</td>
<td>Conducted Susceptibility, Antenna Port, Intermodulation</td>
</tr>
<tr>
<td>CS104</td>
<td>Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals</td>
</tr>
<tr>
<td>CS105</td>
<td>Conducted Susceptibility, Antenna Port, Cross-Modulation</td>
</tr>
<tr>
<td>CS109</td>
<td>Conducted Susceptibility, Structure Current</td>
</tr>
<tr>
<td>CS114</td>
<td>Conducted Susceptibility, Bulk Cable Injection</td>
</tr>
<tr>
<td>CS115</td>
<td>Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation</td>
</tr>
<tr>
<td>CS116</td>
<td>Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads</td>
</tr>
<tr>
<td>CS117</td>
<td>Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads</td>
</tr>
<tr>
<td>CS118</td>
<td>Conducted Susceptibility, Personnel Borne Electrostatic Discharge</td>
</tr>
<tr>
<td>RE101</td>
<td>Radiated Emissions, Magnetic Field</td>
</tr>
<tr>
<td>RE102</td>
<td>Radiated Emissions, Electric Field</td>
</tr>
<tr>
<td>RE103</td>
<td>Radiated Emissions, Antenna Spurious and Harmonic Outputs</td>
</tr>
<tr>
<td>RS101</td>
<td>Radiated Susceptibility, Magnetic Field</td>
</tr>
<tr>
<td>RS103</td>
<td>Radiated Susceptibility, Electric Field</td>
</tr>
<tr>
<td>RS105</td>
<td>Radiated Susceptibility, Transient Electromagnetic Field</td>
</tr>
</tbody>
</table>

**Figure 2.5:** Emission and susceptibility requirements from the military standard MIL-STD-461G.

![Requirement Matrix](image.png)

**Figure 2.6:** Requirement Matrix from the military standard MIL-STD-461G.
The ambient levels must be controlled to maintain the integrity of the measurement. When testing, it is specified on the necessity to measure ambient electromagnetic levels while the EUT is turned off and the auxiliary equipment turned on. As stated in the standard, the measured ambience must be 6 dB below the specified limit.

The frequency range of defining the limits of the radiated emissions is across a wide bandwidth from 30 Hz to 40 GHz. The particular bandwidth for each test depends on the requirement or if specified otherwise, on the operating frequency range of the EUT. The particular frequency range in interest is defined by on-board scientific equipment. The curve of the limit level may vary on a single test which depends on the power supply levels and the platform the EUT is intended for, e.g. internal or external placement on a ship, aircraft, spacecraft, submarine or ground machinery. In addition, depending on the platform the electrical subsystem is intended to be used on, the requirement matrix specifies, as seen in figure 2.6, which are applicable.

The procedure for performing each test is described in great detail, starting with referring to the proper setup in terms of placement and equipment, defining calibration methods prior to the actual measurement procedure along with the limit levels, and finishing with data presentation and analysis.

2.5.1 Conducted Emissions
Conducted emissions imply that electromagnetic energy is created in an electronic device and is coupled to its power cord. The main reason of the conducted emission test is to verify that the conducted noise on the power cables of the EUT does not disturb the voltage distribution along the power bus on the whole platform. Therefore, the limits of the conducted emissions are measured in volts. If the system proves to be incompatible, i.e. emission levels are above the specified limit level, corrective actions are taken before the final system assembly. For measuring the emissions coming from the EUT, the setup requires an oscilloscope, a LISN, a signal generator for calibration and a ground plane. In addition, the EUT and LISNs are expected to be in a shielded enclosure. In the ECSS Standard, a current probe on the neutral line is used to measure emissions between the EUT and LISN. However, the military standard requires a voltage probe measuring from the output port of the LISN.

2.5.2 Radiated Emissions
Radiated emissions measure intentional and unintentional by-products that are radiated from the equipment to protect the on-board receivers and sensors or units
sensitive to magnetic induction from unintentional transmitters. Examples of intentional frequencies are expected radiations from the system clocks, oscillators, coupling paths, power switching or RF subsystems which may reveal even higher radiated emission levels. Moreover, at the proximity of slits on the chassis, more prominent discharges can be documented. Unintentional radiated emissions can be considered as by-products in the form of harmonics coming from digital signals such as the communication bus.

Typically, radiated emission requirements are specified for satellite equipment that is intended to be turned on during launch, to avoid interference within the frequency bands designated for the launcher (ECSS-E-ST-20-07C, 2012). For other cases, the ECSS standard specifies that radiated emissions at low frequency field are measured only for characterisation and the obtained results are used to verify compliance with system level requirements. In case for the military standard, radiated emission requirements in the magnetic field for spacecrafts are not mandatory to be compliant with. However, similar to the ECSS standard, the emission levels depend on ensuring compliance with the whole system. For example, the magnetic field emission limits may depend on sensors on-board the spacecraft such as magnetometers, whereas near field electric field emission measurements can help prevent capacitive crosstalk between cables.

Overall, similar to the conducted emission tests, radiated emissions pose a complementary requirement to susceptibility tests to ensure compatibility with the expected magnetic or electric fields.

2.5.3 Conducted Susceptibility

This measurement verifies that the EUT performs without anomalies or degradation when the Direct Current (DC) power bus, antenna ports or even the chassis experience a disturbance such as a ripple. The ripple is generated by a signal which is injected to the respective input and the system’s reaction is recorded. Most of the tests use an inductive probe which couples the energy on to the EUT hardware. Compared to the previous versions of the MIL-STD-461, the most recent one features conducted susceptibility tests in case of lightning-induced transients (CS117) and electrostatic discharge effects from personnel (CS118). Same concept susceptibility tests are defined in the ECSS standard as well.
2.5.4 Radiated Susceptibility

The aim of the requirement is to guarantee that in the likely case of electric or magnetic field emissions from the environment or neighbouring subsystems, the EUT does not show anomalies or failures in its performance nor shows signs of degradation. The limits are taken from worst-case scenarios in electromagnetic field radiation from e.g. power transformers or antenna transmissions from the launch site or the spacecraft itself (Mallette and Adams, 2011). Examples for testing the use case is when a sensor is located at the main beam or sidelobes of a transmitting antenna on the spacecraft, or when the shielding integrity of the whole assembly needs verification.

Given the scope of the thesis, only emission measurements are done therefore susceptibility tests are not the focus of this project. The emission measurements include conducted emissions on the thruster’s power leads including returns, and radiated magnetic field emissions in the near field.

2.5.5 Standard Setups

When conducting measurements, the placement and setup of all the equipment is important. The aim of the setup is to achieve repeatability when moving from one lab setup to another. The setup requirements vary within the standard depending on the size of the EUT, i.e. whether it is small enough to be placed on a table or the dimensions require the EUT to be placed next to the table while the chassis is still grounded to the ground plane.

An RF anechoic chamber is a room where the electromagnetic waves are completely absorbed by the walls, giving the effect of an infinitely large room where the measured waves originate only directly from the source which eliminates noise from reflections or external sources. The RF anechoic chamber is similar to an acoustic anechoic chamber, but the difference lies in the material and geometry of the wall covers, i.e. the RF anechoic chamber’s interior surface is covered with radiation absorbent material. Radiative emission and susceptibility tests are performed in these chambers to avoid spurious signals and reflections from the setup disrupting the accuracy of the measurement.
Reverberation chambers are used for measuring the effectiveness of shielding when performing radiated susceptibility tests, as the goal is to create with a transmitting antenna various modes for specific standing wave patterns in the chamber (Corona, Ladbury, and Latmiral, 2002). Contrary to the anechoic chamber, the interior of the reverberating chamber is meant to reflect any signal, hence the requirement to construct everything from metallic material.

Figure 2.7: The AMS-02 is being prepared for testing in the anechoic chamber at the ESTEC Maxwell Test Chamber. Copyright: ESA (2010).

Figure 2.8: A motorcycle being tested in the EM reverberation chamber at Otto-von-Guericke University Magdeburg in Germany. Copyright: Dr. Hans Georg Krauthäuser (2005).
Notice in figure 2.8 on the left side there is a construction with paddles which is called the tuner. The tuner can be mechanically rotated and is used to stir the electromagnetic field inside the chamber, inherently creating a statistically uniform field (Corona, Ladbury, and Latmiral, 2002).

Every standard defines their guidelines on the general test setup. The ECSS Standard does not have specifications on the ground plane's elevation from the floor. The interconnecting cable to the EUT runs separately to the access panel and not in parallel with the power lines as required in the military standard. The table in the military standard must be made of non-conductive material and is covered on top by a plate of conductive material which is grounded. Both, the LISN and EUT, are grounded to the ground plane from the external chassis. There are requirements, as seen in figures 2.9 and 2.10, for distances between devices, elevation from the floor, and separation of interconnecting and power source cables.

Figure 2.9: The general test setup based on the ECSS Standard (ECSS-E-ST-20-07C, 2012).
The LISN is an easy to use coupling and standard impedance device and has a wide application, and has been integrated into most of the commercial and military standards (Morgan, 1994).

In general, the LISN is required to provide a defined impedance control from the power source and ensure test repeatability. With defined impedance control, the EUT can be expected to have a proper supply of AC or DC.

Furthermore, the LISN isolates the experiment from the mains which, in this thesis, is meant as electrical power from the wall outlet and the bench top power supply (72-10495 Tenma). The aim is to always measure noise originating only from the EUT. Thus, by connecting a LISN between the power source and experiment, any RF noise, such as the mains hum, originating from the supply does not affect the EUT nor the measurement. The LISN has three terminals as shown in figure 2.11: two ports meant as a feedthrough path for DC and a coaxial terminal for connecting to a measurement receiver. Conducted emission measurements are taken from the signal output port of the LISN. The readings give the magnitude of any RF noise reflected to the power lines of the experiment.
Figure 2.11: Basic functionality of a LISN with the SMA connector as the output port.

There are various LISNs commercially available where its characteristics depend on which kind of standard it is intended to be used with (CISPR, ECSSS, MIL-STD, etc.). A fully military standard compliant LISNs could be considered excessively expensive upon viewing their seemingly simple circuit design, sold at around 1000 – 3000 euros (TEquipment, 2019).

Figure 2.12: Commercially available LISN for MIL-STD-461 by TEquipment (TEquipment, 2019).

2.6.1 MIL-STD-461G LISN

The following LISN is designed to have a 50 Ω impedance from approximately 300 kHz with a degrading impedance value at lower frequencies which is a by-product of the design. When testing for CE102, there is a correction factor, found in equation 3.1 that accounts for the impedance value of 50 Ω which is not met throughout the bandwidth.

The inductor of the LISN passes DC and blocks RF noise whereas for capacitors
behave oppositely. The 5 Ω resistor acts as a load for the choked RF leakage which prevents the EUT emission readings from being affected by the power supply and defines the impedance value at lower frequencies. The 0.25 µF capacitor is a coupling capacitor to extract the interference signal to the measurement port. The predominant characteristic of the circuit is the 50 µH or 5 µH inductor. The choice between using either of the values depends on the actual length of the power lines for the experiment where 1 m of cable length represents 1 µH.

![LISN Schematic defined in the military standard (MIL-STD-461G, 2015).](image)

Figure 2.13: LISN Schematic defined in the military standard (MIL-STD-461G, 2015).

Devices on small aircraft and motorised vehicles can be estimated to have power cable lengths not longer than 5 m. There are multiple options to construct a LISN as it depends under which standard the measurements are made. As the EUT is requested to prove compliance with the military standard, the device is done accordingly to the MIL-STD-461G requirements as seen in figure 2.13 for tests CE102 and RE101.

2.6.2 ECSS-E-ST-20-07C LISN

The LISN definition in the ECSS-E-ST-20-07C is similar to the LISNs used in the military standard. The schematic accommodates two lines in a single metal enclosure with an inductor of 2 µH by default settings. The 0.1 Ω resistors (value by default) in series with the inductances represent the resistances of the wiring, whereas the parallel resistors of 50 Ω result in a resistance of 100 Ω at high frequencies to mimic the characteristic impedance of the power supply line.
2.7 Summary

It is important to pursue in earnest electromagnetic compatibility, as the effects of EMI can be detrimental to electrical systems used in space. Regulations on EMC have been developed and imposed on electrical equipment for space applications by multiple institutions. Running the test procedure requires a thorough preparation to ensure the measurement equipment and environment meet the set standards which in turn will allow verifiable test results.

A client of ThrustMe has requested to prove electromagnetic compatibility on the NPT30 thruster according to the standard MIL-461G with a list of relevant tests. Before scheduling a visit to the test house in the near future, it was decided to include in-house pre-compliance testing into the development process. The first EMC tests involve testing for conducted emissions on power lines and radiated emissions in the magnetic field which fall into the scope of this project. Given the possibility, circuit boards and additional accessories relevant for creating the setup were ordered and designed, according to the standard’s requirements, such as the LISN and loop sensor.
Chapter 3

APPROACH

3.1 Setup

Two in-house pre-compliance emission measurements based on the military standard MIL-STD-461G were done under the scope of this thesis: CE102 and RE101. They were among the list of EMC tests demanded by one of the customers of ThrustMe. The two procedures for emission measurements fit the scope of this thesis.

Each test requires a basic table setup shown in figure 2.10, a measurement system integrity check followed by the EUT testing as specified in the procedure. The first test measures conducted emissions on power leads including returns from other sources which are not part of the EUT. The second test measures radiated emissions from the equipment enclosure, including electrical cable interfaces but is not applicable to radiation from antennas.

The tests were performed in the facility of ThrustMe at the electronics laboratory where the necessary equipment was available, such as an oscilloscope, signal generator, power supply, antennae, and cabling. Measurements were also taken in the main laboratory where the EUT was placed in the vacuum chamber to test the experiment in a fully operational mode, including plasma inflow where the ions are accelerated across the set of biased grids.

In both tests, the experiment is placed on a wooden table with a metallic ground plane under LISN and EUT which were grounded with a bond strap to the ground plane from their external shielding as specified in the standards. Grounding the units was done through a single-point to avoid ground loops which occur when there are more than one conductive paths between two points. A non-conductive, wooden, plate is placed under the 2 m long cables connecting between the LISN and EUT.

All signal sources and outputs are calibrated in terms of an equivalent Root Mean Square (RMS) value to ensure consistency. For example, if a 88 dB µV unmodulated signal is applied to the receiver, then the receiver must indicate 88 dB µV.

An oscilloscope (Rigol DS4024) is used as a measurement receiver for each setup. In order to achieve the desired frequency span, based on the Nyquist-Shannon sampling theorem, the sampling frequency must be greater than double the span value. As the
The highest frequency value in interest is 10 MHz for CE102 and 100 kHz for RE101, a sampling rate of 50 MS/s (megasamples per second) with 700,000 points per sample is chosen on the oscilloscope, under the Acquire settings. This would give an [Fast Fourier Transform (FFT)] range of 0 to 25 MHz. The frequency resolution of the FFT is the sampling rate divided by the number of points. Therefore, in the following setup, the distance in Hz between two adjacent data points in FFT is 71.4 Hz.

### 3.1.1 LISN Design

As the military standard does not specify the exact values on the impedance curve as seen in [3.5a] when the output is loaded with 50 Ω, a simulation is done in LTSpice where the schematic, seen in figure [3.1] is based on the specification of the [LISN] in the military standard. The 50 Ω resistor, marked as R3, in parallel with the 1 kΩ is used for simulation only and represents the internal impedance of the measurement port. Therefore, impedance is measured across the R3 resistor.

![Figure 3.1: LISN Schematic set up in LTSpice to simulate impedance values within the required bandwidth.](image)

As mentioned in subsection [2.6] the inductor of the [LISN] can either be 50 µH or 5 µH. For the following tests, worst-case scenario is preferred as the power lines may be longer than 5 m when the payload is on the launchpad.
Figure 3.2: LISN PCB Design drawings made in KiCAD.

Figure 3.3: Manufactured LISN. The positive power line goes through LISN+ and the negative line through LISN-. Both boxes are shielded with aluminium tape.
Usually LISNs have a metal enclosure around the circuitry for shielding purposes, thus when constructing the LISN for measurements, the plastic casing is covered with aluminium tape. The adhesive side of the aluminium tape is non-conductive, therefore a strip of copper tape, with its conductive surface facing the aluminium tape is taped across the shielding as seen in figure 3.4.

![Conductive "bandaid" with adhesive sides stuck to each other.](image1)

![Electrical connection of the two case sides of the LISN with the "bandaid".](image2)

**Figure 3.4:** Conductive "bandaid" made of copper and aluminium tape to electrically bond the whole shielding made of aluminium tape

The conductivity across the casing is verified with a multimeter in continuity mode. Continuity mode measurements were repeated after connecting the LISN to the ground plane with copper tape and verifying an electrical short from the surface of the LISN to any point on the surface of the ground plane. Each LISN circuit is intended for one power line: live and neutral wire.

The obtained impedance values from the simulation and measurement at the four specified frequencies are shown in table 3.1. Comparing measured LISN impedance with the simulated results, by removing the R1 resistor from the circuit, the deviation from the required impedance decreases at a lower frequency of 10 kHz. The measurement is done across the 1 kΩ resistor with combination of the 50 Ω impedance on the measurement receiver, leaving the two parallel resistances to be equivalent to 47.6 Ω.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Impedance Required</th>
<th>Measured</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kHz</td>
<td>4.6 Ω</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>100 kHz</td>
<td>24.6 Ω</td>
<td>25.26 Ω</td>
<td>2.7%</td>
</tr>
<tr>
<td>2 MHz</td>
<td>47.45 Ω</td>
<td>47.75 Ω</td>
<td>0.6%</td>
</tr>
<tr>
<td>10 MHz</td>
<td>47.6 Ω</td>
<td>47.71 Ω</td>
<td>0.23%</td>
</tr>
</tbody>
</table>

**Table 3.1:** The LISN impedance with the measured impedance shown in blue and the required impedance marked in black.

The miniVNA PRO used for measuring the impedance values of the LISN has a bandwidth range of 100 kHz – 230 MHz, therefore no results could be obtained for frequencies lower than 100 kHz. If measurements could be taken at such low frequencies, the results would provide a better insight on whether the power input side of the circuit would require modifications as the impedance on lower frequencies depends on the resistance between 8 µF and ground.

![Figure 3.5](image)

(a) LISN Impedance from (MIL-STD-461G, 2015). (b) Measured LISN Impedance with the miniVNA PRO.

**Figure 3.5:** The LISN impedance requirement is shown on the first figure and the measured impedance on the second image.

In addition, as the VNA’s Device Under Test (DUT) port does not have an output impedance of 50 Ω, an equivalent resistor is placed in parallel with the 1 kΩ resistor of the LISN just as can be seen in the LTSpice simulation schematic in figure 3.1. The latter procedure was done only for the sake of measuring with the VNA and is not used in the real setup, as the 50 Ω impedance is set on the oscilloscope’s port.

Given that the deviance of the constructed LISN is well within the 20% tolerance margin of the standard LISN impedance requirement, the following tests can be performed.
3.2 Setup of Conductive Emission tests: CE102

The following Conductive Emission test’s requirement is applicable in a frequency range from 10 kHz to 10 MHz on power leads and returns which power the EUT externally. External power source (AC or DC) can be from a battery on-board the spacecraft or the umbilical power cable from the launcher. The source voltage used for the EUT in the following test is 28V DC as it is the highest input voltage allowed according to the specifications of the NPT30 thruster.

3.2.1 CE102: Measurement system integrity check

Before starting the measurement, the LISN needs a system check and be calibrated if necessary. Calibration assures that the measurement equipment is working properly with sufficient sensitivity for signals as much as 6 dB below the applicable limit seen in figure 3.7. By connecting the system accordingly to figure 3.6 which is specified in the military standard procedure, the signal from the EUT side of the LISN is applied with the signal generator.

![Figure 3.6: CE102 Measurement system integrity check setup diagram from (MIL-STD-461G, 2015).](image)

The exact procedure varies depending on the measurement the LISN is checked for. In this case, the system integrity check is done accordingly to the CE102 requirement. Both ports of the LISN are monitored with an oscilloscope to accurately verify
whether the insertion loss from the LISN is well within the limits. The 20 dB attenuator between the LISN and measurement receiver is used to protect the latter from damaging power switching or interference transients.

![Figure 3.7](image.png)

**Figure 3.7:** CE102 limit for Space applications taken from (MIL-STD-461G, 2015).

### 3.2.1.1 Method

The calibration signals are specified in the calibration standard for CE102. As the calibration procedure states, the magnitude values have to be chosen at least 6 dB below the specified limit following the basic curve as seen in figure 3.7 since the EUT uses source voltage of 28V. At ~6 dB the magnitude of the signal is at half power of the limit level. The signal input values are shown in table 3.2 and measurements are performed for each case.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5 kHz</td>
<td>88 dB μV 25 mV</td>
</tr>
<tr>
<td>100 kHz</td>
<td>68 dB μV 2.5 mV</td>
</tr>
<tr>
<td>1.95 MHz</td>
<td>54 dB μV (60*) 0.5 mV (1.0*)</td>
</tr>
<tr>
<td>9.8 MHz</td>
<td>54 dB μV (60*) 0.5 mV (1.0*)</td>
</tr>
</tbody>
</table>

**Table 3.2:** Signal levels applied to the output terminal of the LISN for calibration measurements.

*The signal generator in the ThrustMe laboratory cannot provide a signal at such a low magnitude in the specified frequency, therefore 1mV is used.*
3.2.1.2 Verification

As the setup has two LISNs, one for each line, two measurement results are presented in table 3.3 and 3.4. In the case of LISN+, the specified frequency spectrum is visualised in figure 3.8.

(a) Calibration signal of 25mV at 10.5 kHz.  
(b) Calibration signal of 2.5mV at 100 kHz.  
(c) Calibration signal of 1mV at 1.95 MHz.  
(d) Calibration signal of 1mV at 9.8 MHz.

Figure 3.8: CE102 Calibration measurements on LISN+. The red line indicates the limit for systems using 28V, the green line is 6dB lower than the limit value. Measurement data is presented in blue which shows the signal magnitude across the spectrum and the red circular marker indicates the maximum peak.

The marked maximum peaks every figure represents the calibrated signal injected into the LISN from the EUT side by the signal generator. The results above 100 kHz show reconcilable values, whereas at lower frequencies the error margin is over 20 dB µV. Given the limitation of impedance measurements at low frequencies, mitigation methods for this problem can not be blindly solved. When performing measurements this setback is taken into account when performing actual measurements and in the following iterations of LISN development, the circuit is modified.
Table 3.3: Signal levels measured at the output terminal of the LISN+. The difference between applied and measured signal is shown in the right column.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>LISN+ Magnitude (Vpp)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5 kHz</td>
<td>65.48 dB µV</td>
<td>22.52 dB µV</td>
</tr>
<tr>
<td>100 kHz</td>
<td>66.53 dB µV</td>
<td>1.47 dB µV</td>
</tr>
<tr>
<td>1.95 MHz</td>
<td>59.46 dB µV</td>
<td>0.54 dB µV</td>
</tr>
<tr>
<td>9.8 MHz</td>
<td>59.28 dB µV</td>
<td>0.72 dB µV</td>
</tr>
</tbody>
</table>

Table 3.4: Signal levels measured at the output terminal of the LISN-. The difference between applied and measured signal is shown in the right column.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>LISN- Magnitude (Vpp)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5 kHz</td>
<td>63.29 dB µV</td>
<td>24.71 dB µV</td>
</tr>
<tr>
<td>100 kHz</td>
<td>65.93 dB µV</td>
<td>2.07 dB µV</td>
</tr>
<tr>
<td>1.95 MHz</td>
<td>59.46 dB µV</td>
<td>0.54 dB µV</td>
</tr>
<tr>
<td>9.8 MHz</td>
<td>59.08 dB µV</td>
<td>0.92 dB µV</td>
</tr>
</tbody>
</table>

3.2.2 CE102: Measurement

As the LISN is verified to be within the required specifications, the experiment can be set up to proceed with measurements. The table setup is made to follow the placement standard as closely as possible with the given facilities. For example, there was no access to a purely wooden table and a Electrostatic Discharge (ESD) workbench table was used. During the measurement, the surrounding equipment not crucial to the process was turned off including the lights to have the lowest ambient noise levels and no personnel present during the data saving process.

3.2.2.1 Setup

The setup for measuring conductive emission levels at the required frequencies includes a LISN, a measurement receiver and data recording device i.e. an oscilloscope, a 50 Ω termination from the positive line LISN and a 20 dB attenuator at the input of the oscilloscope measurement port, a power source, a coaxial cable, and power cables.
3.2.2.2 Method

Two separate test setups were performed where the EUT is placed on the table in a plastic container shielded by aluminium tape. The wires connecting between the EUT and LISN are 2 m long, as specified by the standard, and run partially along a wooden plate on the ground plane.

In order to test the thruster with the activated cathode and plasma flow, the experiment is placed in a vacuum chamber. When conducting the following measurements in a vacuum chamber the limitations of the room did not provide enough space to create the setup according to the specifications in figure 3.10. Therefore the cables were suspended over a crane above the vacuum chamber to avoid additional noise coming from the other cables as seen in figure 3.11. Due to the complexity of the setup, it was not possible to turn off all of the surrounding equipment to avoid additional noise e.g. from the vacuum pump or the vacuum chamber’s sensors like the Langmuir probe.
3.2.2.3 Data Processing

The data is saved as a \texttt{.csv} file on a USB drive which is processed from time domain to frequency domain with FFT using open source software Octave. As required by
the standard, data is presented with the limit level, with the frequency vector in a logarithmic scale in Hz and magnitude in a linear scale yet in the unit dBμV.

A correction factor is applied for the 20 dB attenuator and also the voltage drop due to the 0.25 μF coupling factor on the LISN. The correction factor is defined in equation (3.1) (MIL-STD-461G, 2015).

\[ CF = 20 \log_{10} \frac{\sqrt{1 + 5.60 \cdot 10^{-9} \cdot f^2}}{7.48 \cdot 10^{-5} \cdot f} \]  

(3.1)

where \( f \) is the frequency of interest in Hz.

### 3.3 Setup of Radiated Emission tests: RE101

The requirements of the following radiated emission test measures the magnetic field from equipment, system enclosures and electrical cable interfaces in a frequency range between 30 Hz and 100 kHz. The requirement specifies not to apply to radiation from antennas. RE101 aims to verify that the magnetic field emissions do not radiate in excess of the limit levels shown in figure 3.12.

Considering the placement of the sensor from the EUT, the distance between them is required to be 7 cm. The close distance is intended to analyse near field emissions and consider the results either in mitigating excessive levels or in placement planning when assembling and integrating the spacecraft. Although the distance of 7 cm may be a practical consideration, the distance is electrically short for the intended frequency range. At the near field region, the field structure of the sensor is complex and may be considered sensitive to minor changes in distances, as well as the coupling between the EUT and sensor is more severe (Ma, 1992). The choice of requiring exactly 7 cm has little technical basis besides being decided by the committee to standardise the measurement procedure. The ECSS standard specifies that the DC magnetic field emissions are to be measured at distances three times the size of the EUT with centered dipole approximation. In case smaller distances are needed due to mission requirements, then multiple dipole modelling techniques or spherical harmonics techniques are recommended.

#### 3.3.1 RE101: Measurement system integrity check

Just as the procedure states in the previous CE102 measurement, before starting the measurement, the system needs an integrity check and calibration if necessary. The standard does not include the constructed loop sensor in the procedure, therefore an
additional method was developed to involve the passive measurement device in the system integrity check in order to have complete confidence in the equipment and measured results.

**Figure 3.12**: RE101 limit levels for all Army (including Space) applications from (MIL-STD-461G, 2015).

### 3.3.1.1 Standard Setup

The setup for performing the measurement system integrity check specifies that the signal generator shall be connected to the oscilloscope with a 50 Ω impedance coaxial cable as provided in figure 3.13.
Figure 3.13: RE101 Measurement system integrity check configuration from (MIL-STD-461G, 2015).

3.3.1.2 Standard Method

A calibrated signal level that is 6 dB below the limit level at 50 kHz, is injected from the signal generator to the oscilloscope’s input port. Both devices have internal impedances set to 50 Ω. The aim is to verify that the oscilloscope provides accurate readings.

Figure 3.14: RE101 measurement system integrity check in the lab.
3.3.1.3 Standard Verification

![RE101 Standard Calibration](image)

**Figure 3.15**: RE101 measurement system integrity check results.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Applied</th>
<th>Received</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kHz</td>
<td>103.12 dB pT</td>
<td>103.50 dB pT</td>
</tr>
<tr>
<td></td>
<td>22.50 mV</td>
<td>23.50 mV</td>
</tr>
</tbody>
</table>

**Table 3.5**: RE101 Calibration results. The signal is applied straight from signal generator to the oscilloscope.

Based on Faraday’s law, the applied voltage can be calculated from the defined magnitude of the magnetic field. A calibration signal of 45 mV at 50 kHz is applied from the signal generator. From the Fast Fourier Analysis the equivalent measured magnitude should be 103.12 dB pT and as seen in table 3.5, the measured value is 103.50 dB pT leaving a deviance of 0.38 dB pT. As the limit for maximum deviance is ± 3 dB, the measurement system can be verified to be adequate for further testing.

3.3.1.4 Custom Setup

Even though the measurement system integrity requirements were fulfilled, another verification method is developed. The custom verification system creates a known
magnetic field, making it possible to ensure the integrity of the computational method for determining the measured magnetic field with the receiving coil. A transmitting coil is able to create a strong enough magnetic field that can be estimated based on readings from the current sensor attached to the coil. Both coils are measured and the results compared where the readings should give similar results.

The signal generator (RIGOL DG4062) has outputs limited to 5 V into a 50 Ω load. For this high power application, a power amplifier is required to amplify the driving capability. The amplifier creates higher power (W) by amplifying the current drawn from the power supply.

![Image](image.png)

**Figure 3.16:** RE101 custom measurement system integrity check configuration.

The coil is considered as a solenoid as it has wire wrapped around it with many turns yet is not very long. As current is passed through the coil, it creates a magnetic field inside. The direction of the current flowing through the coil defines the direction of the magnetic field. Ampere’s law allows to calculate the strength of the magnetic field as follows

\[
\int \vec{B} \cdot d\vec{s} = \mu_0 I
\]  

(3.2)

where the integral around a closed path of the component of the magnetic field tangent to the direction of the path equals to permeability \(\mu_0\) times the current
intercepted by the area within the path. To determine the magnetic field at a
distance from the central axis of the coil is shown in Appendix B. The resulting
equation is as follows

\[ B_{total} = \frac{\mu_0 \cdot I_T \cdot n_T}{2} \left( \frac{d + L_T}{\sqrt{(d + L_T)^2 + r_T^2}} - \frac{d}{\sqrt{d^2 + r_T^2}} \right) \]  

(3.3)

where \( B_{total} \) is the magnetic flux at distance \( d \) based on the measured current \( I_T \).
Furthermore, \( \mu_0 \) is permeability of free space, \( n_T \) is turn density of the transmitting
coil and \( L_T \) is the length of the coil with radius \( r_T \).

### 3.3.1.5 Custom Method

The calibration system consists of a transmitting loop coil with the same geometrical
attributes as the receiving coil for the sake of easier alignment along the central axis.
In addition, the transmitting coil has the same amount of turns to remove the need for
additional consideration for the turn ratio. The wire is thicker on the transmitting coil
than on the receiving coil since the transmitter needs to withstand higher currents
due to the coil’s low resistance and given high voltage.

Connecting a coil simply to the signal generator would not suffice as it has an output
impedance of 50 \( \Omega \), meaning it is intended to drive 50 \( \Omega \) loads. A power amplifier
is needed as the load impedance is lower than 50 \( \Omega \).

![Figure 3.17: Audio power amplifier circuit board.](image)

The magnetic field generator consists of an audio power amplifier TDA7264 (ST, 2009)
that can amplify signals within the same frequency range that is applicable
for the test. The application circuit is based on the amplifier’s datasheet where its output pin, destined for a speaker, is connected to one of the leads of the transmitting coil. To increase the electromagnetic driver output current and inherently achieve a stronger alternating magnetic field, the coil is made more resistive by adding two 1 Ω resistors in series.

![Figure 3.18: RE101 Custom Measurement system integrity check setup.](image)

As the magnetic coil is highly inductive, its impedance is reactive meaning the real resistive part of the impedance is close to zero. The transmitting coil does not dissipate thermal power due to its small resistance, thus the real power or heat is radiated inside the AC magnetic coil driver i.e. the audio amplifier, and also in the two added series resistors. Due to the excessive heating a large radiator is attached to the power amplifier and power resistors with a screw and a thermal conductive sheet in between. The radiator allowed the amplifier to be in use for a longer period of time as without it, the device would overheat and distort the waveform in a matter of minutes.

For the following system integrity check, a 5 kHz signal is given to the input of the amplifier. The amplifier operates at a frequency range of 20 Hz to 22 kHz. The input signal at 5 kHz and 250 mV generated enough power to use the system without overheating it. Also, the resulting magnetic field strength level at a distance of 7 cm is relevant to the level of sensitivity of the measurement - around 150 dB pT.
3.3.1.6 Custom Verification

The receiving loop coil is constructed based on the requirements defined in the standard with 36 turns and a diameter of 13.3 cm. Having a resistance of 8.9 Ω between the two ends leaves the electrical properties of the coil well within the margin of 5 – 10 Ω. The following measurements were done by placing the transmitting and receiving coils as close to each other as possible and gradually, one centimeter at a time, increasing the distance between them. The created magnetic field is calculated with Ampere’s law seen in equation B.17 based on current readings and the measured magnetic field with the voltage sensor using Faraday’s law using equation 3.4. The results of both measurements are overlaid in figure 3.19. The calculated magnetic field at a distance of 7 cm is calculated to be 0.042 mT or 152.53 dB pT while the loop sensor measures 0.39 mT or 151.90 dB pT. The receiving coil shows a deviance of 0.63 dB pT which is well below the 3 dB variance margin set by calibration procedures found in the military standard.

![Graph showing magnetic field vs distance](image)

**Figure 3.19:** RE101 custom measurement integrity check results.

Based on the results, it is shown that the measurement method and calculation process are valid with a small deviance which is well within acceptable boundaries.

3.3.2 RE101: Measurement

As the measurement equipment is verified to be within required performance limits, the EUT can be prepared for measurements. The table setup is similar to the CE102
requirement. Ambient measurements were taken prior to turning on the experiment and insured lack of any prominent magnetic field emitting from the environment as seen in the signal in figure 4.4 marked in pink.

3.3.2.1 Setup

The setup for measuring the radiated emissions, shown in figure 3.20 includes where the thruster is powered through the LISN to ensure stable impedance from the power source. The loop sensor is placed 7 cm from the edge of the thruster. An oscilloscope which is validated as an acceptable receiver through system integrity check is used to measure the induced voltage on the coil.

![Figure 3.20: RE101 measurement setup diagram from (MIL-STD-461G, 2015).](image)

3.3.2.2 Method

The chassis of the thruster is grounded to the ground plane and, as seen in figure 3.21 located on the left side of the setup, with the loop sensor placed at a distance of 7 cm. The operational modes of the thruster are controlled from the computer (seen on the left hand side of the figure) via USB CAN bus which has its ground pin also grounded to the ground plane. For each measurement and for every side, the EUT was turned to measure the magnitude of the magnetic field.
3.3.2.3 Data Processing

A current sensor is used to measure and calculate the magnetic field on the transmitting coil. The receiving coil is measured as an open loop with a voltage probe. The measured magnetic field is found with Faraday’s law. According to Faraday’s law, the voltage induced in the receiving coil is due to the changing of the magnetic flux perpendicular to the loop area, as seen in equation 3.4. Note that a Hall effect sensor is not used for this measurement as its working principle depends on the static magnetic field.

\[ V = -2\pi f BA \]  

(3.4)

where \( V \) is the induced voltage on the loop in \( V \), \( f \) is the frequency of interest in \( Hz \), \( B \) is the magnitude of the magnetic field in \( T \) and \( A \) is the loop area \( m^2 \).

The data is saved as a .csv file on a USB drive and plotted in Octave into frequency domain by using the [FFT] function. The results are presented along with the limit levels on a frequency vector in a logarithmic scale in \( Hz \), and the magnitude of the magnetic field in \( dBpT \) in a linear scale.
Chapter 4

RESULTS

The NPT30 model was powered on through the LISNs as specified in the setup requirements to measure conducted noise present on the power supply lines reflected by the EUT. For the conducted emissions, multiple modes of the thruster were measured to achieve a thorough overview of the origins of EMI. Measurements were taken in two setups: inside the vacuum chamber and on a table setup at standard atmosphere.

The radiated emissions are measured on each side of the thruster to have a thorough overview of the emitted magnetic field.

Once the plots have been gathered and concluded, a test report is generated for the engineers of ThrustMe to further analyse the performance of the thruster. The report included a systematic overview on the setup procedure on the test, including information about the voltage supply, oscilloscope’s data acquisition settings, the required specifics of the device that is undergoing the test and a statement whether the EUT passed or failed the test. For measurement traceability and repeatability, a procedure document is written to complement the report and every report includes the directory of the raw data is specified along with the date and name of personnel performing the test.

4.1 Conducted Emissions: CE102

The following results show conducted emission levels on power lines which are measured from the LISN. In this setup, the thruster is placed in a shielded box accordingly to the specifications. The noise levels of the environment were recorded and overlayed with test results for a better understanding of the electromagnetic behaviour of the experiment. The current setup of the thruster uses the CAN bus for mode control and is connected to the computer for mode management via USB port. As the thruster was powered on and in Standby mode, the oscilloscope displayed prominent noise appearing periodically. The muddle was identified as EMI originating from the CAN bus. By connecting the GND pin of the USB connector to the ground plane of the setup, the prominent signal was silenced.

In figure 4.3b, the highest source of noise is coming from the DCDC converters
operating according to its datasheet at switching speeds of 260 kHz which is to be expected from the measurement as the DCDC converters are known sources for electromagnetic noise.

Comparing the results for Operational States between with and without Xenon plasma flow, the thruster’s power lines conduct less prominent emissions at higher frequencies since during plasma flow. It is interesting to see that the highest peak is at the third harmonic in figure 4.3a when the thruster does not have plasma flow activated.

Generally, the overall results show promising information with emission levels below the limit levels.

(a) Ambient.

(b) Standby Mode.

(c) CE102 All systems are on.

Figure 4.1: CE102 test results for NPT30 thruster without plasma load.
Figure 4.2: CE102 measurements on NPT30 inside the vacuum chamber without plasma load.
(a) Plasma Flow Maintenance.

(b) Operational mode.

Figure 4.3: CE102 measurements on NPT30 inside the vacuum chamber with Xenon plasma as load.
4.2 Radiated Emissions: RE101

A loop sensor with defined specifications is used to measure the magnetic field emissions. The standard requires to measure and present results only from the side with the most prominent emission levels. Regardless, every side of the EUT is measured and documented for the sake of having a systematic overview of the device’s magnetic field emission levels. Emission level results from the test can be used to perform radiated susceptibility tests on neighbouring experiments to verify compatibility.

It is interesting to note that the +X and +Z sides of the thruster, seen respectively in figures 4.4c and 4.4e, have a signal value that is lower than the ambient noise. This is due to the design of the chassis where a slit is cut near the corner between the mentioned sides of the thruster. The slit is deliberately made in order to achieve desired control over the RF characteristics in Plasma Flow Maintenance. The resulting radiation pattern around the cut may explain why the signal is dampened to be lower than the ambient magnetic flux.

The readings on lower frequencies are not as detailed as the frequency resolution was set on the oscilloscope to 71.4 Hz.
Figure 4.4: RE101 measurement results on each side of the NPT30 thruster.
Chapter 5

CONCLUSIONS

The increasing reliance on electrical equipment and their ever-increasing sensitivity demands attention to electromagnetic behaviour. A quote by George Santayana "Those who cannot remember the past are condemned to repeat it" can be held true in the branch of designing complex electrical systems with mutual compatibility in mind. Commitment to comply with the standards to ensure EMC remains as part of the success to a space mission.

The in-house pre-compliance measurements showed the option to perform tests based on military standards all while achieving a good estimation on the characteristics of the thruster. As a result, the tests were repeated on separate electrical subsystems to investigate further the origins of the emission peaks. Through this, the engineers at ThrustMe could include mitigation methods into their development process when creating new iterations of the electrical subsystems.

5.1 Reflections on the measurements

The prepared setup environment was made accordingly to the specifications in the military standard, keeping in mind grounding, required distances between units and accessories such as over 2 m long power line cables. With the following setups, conducted and radiated emissions were measured while complying with the standard’s requirements on the measurement method.

However, conducted emission measurements that included the vacuum chamber was more challenging due to less space around it and opportunities to create a cleaner ambient environment as additional external equipment needed to stay on, in order to operate the vacuum chamber and the thruster. All the measurements were taken with an oscilloscope and plotted from time domain to frequency domain with FFT using open source software Octave.

The development of the test hardware such as the LISN strictly followed the requirements imposed by the standard and included verification by measurement to a certain extent i.e. its impedance could be measured at higher frequencies than 100 kHz. The calibration procedure for the CE102 test showed losses in the lower frequency band and would require further modifications to the circuit to provide
accurate readings throughout the defined frequency spectrum.

The radiated emission (RE101) calibration procedure was not convincing enough as it does not include the loop probe. The standard measurement system integrity check included a signal generator creating a calibration signal that is measured by the oscilloscope by directly connecting each other’s input and output ports accordingly via a coaxial cable. Another method was developed to be confident in the equipment’s, i.e. loop sensor’s, performance, measurement procedure, and data processing. A magnetic field is generated by running amplified current through another loop coil. The generated magnetic field at a required distance was measured with sufficient accuracy. The measurements on the emitted magnetic field provided data that can be used to prepare the customer for susceptibility tests and ensure compatibility between the two modules.
Chapter 6

FUTURE WORK

The imposed limitations on time did not allow to develop further improvements on the setup and the equipment. Basis of this thesis, additional follow-up in-house tests can be done such as RE102 which measures radiated emissions in the electric field. The setup requires more consideration for the surrounding environment and receiving antennas.

6.1 Improvements in equipment

The performance of the LISN at lower frequencies can be improved by changing the component values on the power supply side or adding additional filtering if necessary. The modification can be verified with an impedance analyser for frequencies lower than 100 kHz. For a more detailed analysis of the conducted emission test on power lines (CE102), an additional set of LISNs with 5 μH could be produced. As mentioned, the 5 μH inductance represents 5 m of cabling which would be valid for testing a use case for the thruster when in orbit. With representing the in-orbit setup, the cables are not expected to exceed 5 m.

For a more convenient setup procedure, the two separate LISNs can be manufactured to house both circuits with RF shielding between the two circuits in mind. It is important to avoid coupling between the two inductors. In addition, the following design iteration should consider an interface for grounding the chassis to the ground plane.

For measurements on radiated emissions, it would be interesting to get a higher resolution overview on the magnetic field emissions surrounding the ion thruster. It would require a specialised platform or fixture around the experiment, while inside the vacuum chamber, to scan the magnetic field and based on the obtained results generate a heatmap that can be used to further characterise the ion thruster.

6.2 Improvements in workflow

The software can be improved to speed up the measurement process and report generation. By implementing a Graphical User Interface (GUI), any personnel able to assemble the setup can perform data acquisition without being familiar with the
code. The data analysis procedure is done by manually inserting the directories of the raw data into the data array. The location for the plot figures is inserted in the same manner. The GUI would request to select the standard, the raw data and the directory for saving the figures in a preferred format. Another option can be connecting the oscilloscope directly to the computer via an ethernet cable. This can give the possibility to perform real-time readings on the measurements with the benefit of speeding up the data presentation process.

Besides, the workflow can be automated further by adding a feature that can export a report and display all the measurements in a single PDF document. As it is interesting to compare how the thruster behaves before and after implementing mitigation methods, it is useful to include a function that allows comparing two results with each other.


Corona, Paolo, John Ladbury, and Gaetano Latmiral (2002). “Reverberation-chamber research-then and now: a review of early work and comparison with current understanding”. In: IEEE transactions on Electromagnetic Compatibility 44.1, pp. 87–94.


Appendix
% Purpose: Data analysis with Fast Fourier Transform (FFT) for EMC pre-compliance test based on MIL-STD-461G
% Equipment: Oscilloscope Rigol DS4024
% LISN 50uH
% Version: 1.0, March 2019
% Author: Siiri Talvistu

clear all
close all

% Sampling frequency of oscilloscope
% must be concurrent with actual measurement
Fs = 50*10^6;

%% INPUT:
% Measured data files
data =['';];

% FFT as many times as there are files in 'data'
A = rows(data);

%% Saving plots to a directory
% TO SAVE '1' or NOT TO SAVE '0'. That is the question.
saveFile = 0;

% SAVE AS. The saved title includes also a date and iteration % sequence number
fileTitle = 'CE102_';

% SAVE LOCATION. Needs to be an already existing folder
filePath = ''; 

for numberOfFiles = 1:A 
% Fast Fourier Transform of measured data 
[fVec, SignalMagnitudeCorrection, signalPeak, signalPeakFreq, 
  signalPeakIndex] = CE102FFT(Fs, numberOfFiles, data); 

% The first row on data is considered as ambient measurement 
% and is plotted on every graph 
if (numberOfFiles == 1) 
  ambient = SignalMagnitudeCorrection; 
endif 

% Plot figures of all given 'data' files in logarithmic scale 
CE102results(fVec, SignalMagnitudeCorrection, numberOfFiles, 
  ambient, saveFile, signalPeak, signalPeakFreq, fileTitle, 
  filePath); 
endfor 

---

**Listing A.2: CE102FFT.m**

% FFT calculation based on results from the oscilloscope 
function [fVec, SignalMagnitudeCorrection, signalPeak, 
  signalPeakFreq, signalPeakIndex] = CE102FFT(Fs, numberOfFiles, 
  data) 

% Analyse all the files in 'data' 
M = csvread(data(numberOfFiles, 1:end)); 

% Amplitude [V] and Sequence 
amplitude = M(3:end,2); 
sequence = M(3:end,1); 

%Set zero pad depth (Radix 2); 
zeroPadDepth = 0;
% Remove DC component from the data
amplitude = amplitude - mean(amplitude);

% RMS of peak value, Requirement in the MIL-STD
amplitude = amplitude/sqrt(2);

% Length of FFT to be same as Sampling frequency or higher.
% With the equal value of measured points the results are most
% accurate (tested with signal generator)
nfft = length(amplitude);

% Fast Fourier Transform with padding of zeros so that
% length(Signal) is equal to nfft
Signal = fft(amplitude, nfft);

% Takes only one side
Signal = Signal(1:nfft/2 + 1);

% Take magnitude of FFT of Signal
SignalMagnitudeAbs = abs(Signal);

% Normalisation and taking into account the total power
SignalMagnitude = SignalMagnitudeAbs/nfft;

% Frequency Vector
fVec = (Fs/2)*linspace(0, 1, nfft/2 + 1);

% Correction factor that accounts for the 20dB attenuator and
% voltage drops across the coupling capacitor in the LISN
CF = (((1+(5.6*10^(-9)).*fVec.^2).^0.5)./(fVec.*7.48*10^(-5)))
  ;
CFt = CF.';
SignalMagnitudeCorrection = SignalMagnitude.*CFt;

% Conversion from V to dBuV
SignalMagnitudeCorrection = 20*log10(SignalMagnitudeCorrection.*10^6);

% Maximum peak value between 10kHz - 30MHz
fVecLength = columns(fVec);
f_low = 10*10^3;
step1 = fVec(1,2); %119.21Hz
stepLast = fVec(1, end); %62.5MHz
% percentage of 10kHz from 62.5MHz
fVecStart = f_low*100/stepLast;
% Sequence number around 10kHz
fVec10 = fVecLength*fVecStart/100;
% integer of sequence number at 10kHz
fVecStartIndex = floor(fVec10);
% Sequence number around 31.25MHz
fVecEndIndex = floor(fVecLength/2);
fVecEnd = fVec(1, fVecEndIndex); % 31.25 MHz
SMC = SignalMagnitudeCorrection(fVecStartIndex:fVecEndIndex, 1);
% Location of peak
[signalPeak signalPeakIndex] = max(SMC);
signalPeakFreq = fVec(1, fVecStartIndex+signalPeakIndex);
endfunction

Listing A.3: RE101FFT.m

% The FFT calculation based on results obtained from the
oscilloscope (Rigol DS4024). The correction factor is taken
into account as specified in MIL-STD-461F Appendix A on page
209 for a 50uH LISN.
function [fVec, MagneticField, signalPeak, signalPeakFreq,
signalPeakIndex, B, maxamp] = RE101FFT(Fs, numberOfFiles,
data)

% Analyse all the files in 'data'
M = csvread(data(numberOfFiles, 1:end));
% Voltage Amplitude [V] and Sequence
amplitude = M(3:end,2);
sequence = M(3:end,1);

% Number of turns on the receiving coil based on requirements
N = 36;
% Diameter of the receiving coil
r = 0.133/2;
% Surface
A = pi*r^2;
% Distance from center
z = 0;
\[ u_0 = 4*\pi*10^{-7}; \]
f = 5000;

% Set zero pad depth (Radix 2);
zeroPadDepth = 0;

% Remove DC component from the data and take RMS
amplitude = amplitude - mean(amplitude);
amplitude = amplitude/sqrt(2);
maxamp = max(amplitude);

% Length of FFT to be same as Sampling frequency or higher. With
% the equal value of measured points the results are most
% accurate (Tested with signal generator) nfft = 2^((nextpow2( 
% length(amplitude)))+zeroPadDepth);
nfft = length(amplitude);

% Fast Fourier Transform with padding of zeros so that
% length(Signal) is equal to nfft
Signal = fft(amplitude, nfft);

% Takes only one side
Signal = Signal(1:nfft/2 + 1);
% Take magnitude of FFT of Signal
SignalMagnitudeAbs = abs(Signal);

% Normalisation and taking into account the total power (x2)
SignalMagnitude = SignalMagnitudeAbs/nfft;

% Frequency Vector
fVec = (Fs/2)*linspace (0, 1, nfft/2 + 1);

% Faraday's law for Receiving coil's Magnetic field [Wb]
B_flux = (SignalMagnitude)./(fVec'.*2*pi*N);

% Magnetic flux density, T = Wb/m^2 [T]
B = B_flux/A;

% Converting T to dBpT (required for data presentation)
MagneticField = 20*log10(B*10^12);

% Maximum peak value from an range of interest
MagneticFieldMax = MagneticField(75:5000);

% Location of peak
[signalPeak signalPeakIndex5] = max(MagneticFieldMax);
signalPeakIndex = signalPeakIndex5+75;
signalPeakFreq = fVec(1, signalPeakIndex);
endfunction
Appendix
**Appendix B**

**DERIVATION OF AMPERE’S LAW**

To determine the strength of the magnetic field, Ampere’s law can be used as follows

\[ \int \vec{B} \cdot d\vec{s} = \mu_0 I \]  
(B.1)

\[ BL = \mu_0 \text{I} n L \]  
(B.2)

\[ B = \mu_0 \text{n} I \]  
(B.3)

where \( I \) is current through the wire and \( n \) the number of coils per meter.

To find the magnetic field at a distance from the center of the coil, \( \vec{dB} \) is considered as a ring of current and integrated over all coils to find the magnetic field. By applying the principle of superposition, a coil of wire with a radius \( R \) carries current \( I \) and creates a magnetic field at point \( P \). Magnetic field at the top of the loop or the edge of the coil is

\[ \vec{dB} = \frac{\mu_0 I}{4\pi} \frac{ds \times \hat{r}}{r^2} \]  
(B.4)

and is pointing downwards to one side and the magnetic field at the opposite side of the loop is pointing upwards in the same direction, inherently cancelling each other out and leaves

\[ dB_{\text{H}} = \frac{\mu_0 I}{4\pi} \frac{ds}{D^2 + R^2} \frac{R}{\sqrt{D^2 + R^2}} \]  
(B.5)

By integrating over every segment over the wire, the total magnetic field is
\begin{align*}
\vec{B} &= \int dB_H \\
\frac{dB_H}{dB_H} &= \frac{\mu_0 I}{4\pi} \frac{R}{(D^2 + R^2)^{3/2}} \int ds \\
\frac{dB_H}{dB_H} &= \frac{\mu_0 I}{4\pi} \frac{R}{(D^2 + R^2)^{3/2}} \cdot 2\pi R \\
\frac{dB_H}{dB_H} &= \frac{\mu_0 I}{2} \cdot \frac{R^2}{(D^2 + R^2)^{3/2}} \\
\end{align*}

which results in the magnetic field along the axis of a single loop. To find the magnetic field along the axis of the solenoid, it must be integrated across all the loops. As a section of the solenoid length $dx$ is considered with the total current around the solenoid in that section results as

\begin{equation}
I_{total} = I(n \cdot dx)
\end{equation}

where the section is located at a distance at a sum of $D$ (distance from the point) and $x$ (distance from the edge) from point $P$. Therefore,

\begin{equation}
B_{total} = \frac{\mu_0 Idx}{2} \cdot \frac{R^2}{((D + x)^2 + R^2)^{3/2}}
\end{equation}

the total magnetic field at point $P$ which is at a distance $D$ away from the edge of the solenoid is

\begin{equation}
B_{total} = \int_{x=0}^{x=L} \frac{\mu_0 Idx}{2} \cdot \frac{R^2}{((D + x)^2 + R^2)^{3/2}}
\end{equation}
\[ B_{\text{total}} = \frac{\mu_0 I n R^2}{2} \int_{x=0}^{x=L} \frac{dx}{((D + x)^2 + R^2)^{\frac{3}{2}}} \]  

(B.13)

while simplifying to \( z \) being the sum of \( D \) and \( x \),

\[ B_{\text{total}} = \frac{\mu_0 I n R^2}{2} \int_{z=D}^{z=D+L} \frac{dz}{(z^2 + R^2)^{\frac{3}{2}}} \]  

(B.14)

as the integral can be done as

\[ \int \frac{dz}{(z^2 + R^2)^{\frac{3}{2}}} = \frac{z}{R^2 \sqrt{z^2 + R^2}} \]  

(B.15)

therefore

\[ B_{\text{total}} = \frac{\mu_0 I n R^2}{2} \cdot \frac{1}{R^2} \left( \frac{z}{\sqrt{R^2 + z^2}} \right)_{D}^{D+L} \]  

(B.16)

\[ B_{\text{total}} = \frac{\mu_0 I n}{2} \cdot \frac{D + L}{\sqrt{(D + L)^2 + R^2}} - \frac{D}{\sqrt{D^2 + R^2}} \]  

(B.17)

where \( R \) is the radius of the solenoid.