University of Southern Queensland

Faculty of Health, Engineering & Sciences

Low-investment EMI pre-compliance for COTS technology insertion into submarine combat systems

A dissertation submitted by

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Abstract

A modern submarine's combat system is largely dependent on commercial off the shelf (COTS) computer technology as a means of cheaply adopting the latest, high-performance, commercially developed and qualified systems to maintain capability. COTS technology is not normally designed for military use, nor is it necessarily compliant to military standards for electromagnetic interference (EMI), such as MIL-STD-461G.

A gap analysis, based on a comparison of commercial and military EMI standards, showed that there is no guarantee of COTS EMI compliance to this military standard.

Formal compliance testing at a certified test house is almost prohibitively expensive for purposes of early experimentation and component evaluation. This is due to the highly controlled, calibrated and specialist nature of such facilities. Because of this, they are normally only used for final compliance testing prior to acceptance of new designs into service.

In order to reduce the risk of a compliance failure, pre-compliance testing should take place prior to and even during system design. Evidently, a need exists for a low-investment and practical test protocol to verify the EMI performance of such COTS equipment against the applicable military EMI standards.

Background research was undertaken into the historical development of current commercial and military EMI standards, the trend and motivation for the use of COTS in the defence environment, as well as the mechanisms and theory of EMI design as applied to the submarine. This research was critical in the development of a gap analysis procedure as well as the development of low-cost and practical alternatives to formal EMI testing with simplified tests as pre-compliance test protocols.

The two major outcomes of this project are:

1. A clear understanding of commercial non-compliance to the military EMI standard.

2. The design of test hardware and calibration techniques with the use of general test equipment to undertake practical EMI pre-compliance tests readily in a typical development laboratory facility.

Due to resource and time limitations, the radiated emissions test design was limited to a span of 1 GHz. Further work is needed to expand the project out to the full 18 GHz military span of interest. Comparisons of experimental results against certified test house results would be most useful to ultimately prove or disprove this concept.

While COTS computer technology is generally sought after to provide low-cost and high capability to defence, commercial EMI standards do not comply with military requirements. It is necessary and eminently possible to undertake low-cost and practical pre-compliance testing as part of a product or system design.

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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

L. Colagiuri

[redacted]

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I dedicate this work in loving memory of my mother, Anna.

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L. Colagiuri

Contents

List of Figures

List of Tables

Nomenclature

AC	Alternating Current
ACMA	Australian Communications and Media Authority
AM	Amplitude Modulation
A-RCI	Advanced Rapid COTS Insertion
AV	Average
CE	Conducted Emissions
CISPR	International Special Committee on Radio Interference
CMS	Combat Management System
COTS	Commercial Off The Shelf
CS	Conducted Susceptibility
DC	Direct Current
DoD	Department of Defense (United States of America)
E-field	Electric field
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EU	European Union
EUT	Equipment Under Test
FASA	Federal Acquisition Streamlining Act
FCC	Federal Communications Commission
FM	Frequency Modulation
FSPL	Free Space Path Loss
HF	High Frequency
H-field	Magnetic field
ICT	Information and Computer Technology

IEC	International Electrotechnical Commission
ITE	Information Technology Equipment
ITU	International Telecommunications Union
LISN	Line Impedance Stabilisation Network
LPDA	Log-Periodic Dipole Array
MEN	Multiple Earth Neutral
MIL-SPEC	Military Specification
OEM	Other Equipment Manufacturer
PK	Peak
PL	Path Loss
PRF	Pulse Repetition Rate
QP	Quasi-Peak
RBW	Resolution Bandwidth
RE	Radiated Emissions
RFI	Radio Frequency Interference
RS	Radiated Susceptibility
TV	Television
UHF	Ultra High Frequency
VBW	Video Bandwidth
VHF	Very High Frequency
VLF	Very Low Frequency

Chapter 1

Introduction

Commercial off the shelf (COTS) Information and Computing Technology (ICT) equipment is more commonly being adopted in submarine combat systems as this allows for low-cost technical refreshment of the Combat System with state-of-the-art computational and data handling technology. However, the adoption of COTS in a military environment introduces risks, that if not managed, can compromise the usability of such solutions. One of these risks is that of electromagnetic interference (EMI) (Dixon 1996, Dixon 1997, Dixon 1998, Dhingra & Nara 2006).

This project is concerned with identifying the gaps between commercial and military EMI standards in order to assess any areas of potential risk of non-compliance with the military EMI standards, which may prohibit the insertion of COTS equipment. Further, in order to evaluate such COTS equipment, this work is concerned with developing a low-cost means of measuring the EMI emissions levels of COTS equipment such that they may be quantified and compared to the limits set by military standards.

A combat system is a completely integrated electronic system for the detection, classification and possible engagement of potential threats. In a submarine, the Combat System integrates Sonar, Electronic Warfare and other tactical data feeds into a command and control computational system, which presents a tactical picture to the submarine's commander. As illustrated in Figure 1.1, today's submarine combat systems are very computer-centric, the dark grey highlighted area is what is known as the Combat Management System (CMS). A CMS supports many co-related processes managing a potentially huge amount of real-time data including navigational information, sonar signal processing, strategic and tactical analyses, defensive counter-measure control and, of course, weapons management and fire-control (Schmid & Crowe 2001).

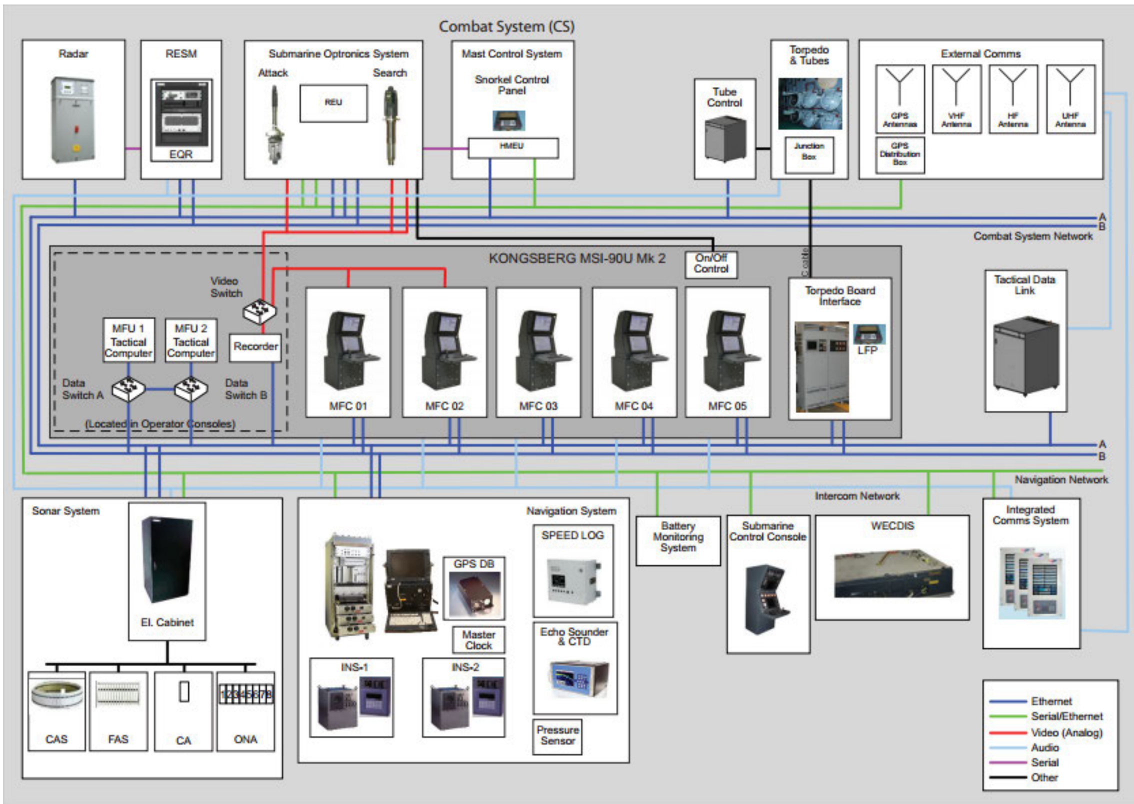


Figure 1.1: A typical submarine combat system physical architecture (www.Kongsberg.com)

1.1 Background

Any electrical and electronic technology used in the military must be able to withstand the rigours of the typical military or "mission" environment. Among the many environmental stresses that such equipment must endure, it must also withstand electromagnetic (EM) stresses and meet EM performance levels. One such area is known as Electromagnetic Compatibility (EMC), which is the term given to the state in which relatively closely located electrical and electronic circuits, equipment and systems can operate harmoniously, within a given environment, without detrimental interaction or interference due to their mutual electromagnetic emissions and sensitivities.

In the case where electromagnetic incompatibility exists between circuits, equipment or systems, there is said to be EMI emitting from one or more items which has coupled into and affected the performance of other items or systems. This coupling, which may be conducted or radiated or both, causes the presence of undesirable voltages or currents of sufficient amplitude to adversely affect equipment performance (Keiser 1979). Hence, there are rigid military EMI standards imposed on such equipment destined for use in the military environment (Mazzola 2009). These standards place limits or controls on the levels of conducted and radiated emission and susceptibility allowed for such circuits, equipment or systems. Such items emitting EMI beyond these limits or that are susceptible to emissions below these limits are said to be non-compliant with these standards.

For example, in the specific case of a platform such as a submarine, compliance is essential due to the close proximities (as seen in Figure 1.2) and interaction of equipment and systems as well as the critical nature of the functions they perform. Functions such as navigation, propulsion, threat sensing and avoidance, weapons targeting and control are all safety critical and depend completely on the unhindered operation and performance of the various, highly integrated electrical and electronic systems deployed on such a platform.

Figure 1.2: Image of operators manning the Combat System consoles of the Australian COLLINS Class Submarine (www.navy.gov.au)

Historically, the global military market was one of the key sponsors of electrical and electronic technology developments and provided most of the investment and most of the demand for, what was then, the leading edge or state-of-the-art technology. These developments were governed by the various, respective military standards for specific performance across many areas, including EMI. However, since the end of the Cold War and the development of the modern, commercially driven technological age, much of the state-of-the-art is now commercially backed and targeted at the very large and profitable consumer and commercial markets, especially in the field of ICT (Guertin & Miller 1998, Kerr, Phaal & Probert 2008). This has meant that commercial technological advances are made at a much faster rate in comparison to what the historical military sponsorship could achieve. Because of high volume mass production, commercially designed and manufactured technology is typically much cheaper, in more plentiful supply and always up to date due to non-military market forces.

In the modern day, the militaries of the world have generally smaller budgets for technology development and typically demand the use of such COTS technologies to replace their expensive, difficult to support, bespoke and rapidly obsolescent, legacy systems (Kerr et al. 2008). Moreover, there are still needs for bespoke military technology in specialist, non-commercially driven areas such as weapons, some sensor technologies and electronic warfare, to name a few. This means that where COTS can be used, it must be able to maintain compatibility with various specialist military technologies, i.e. it must be compliant or be made compliant with military EMI standards.

1.2 Problem space

Figure 1.3 shows an example of a typical piece of COTS ICT equipment. The ability to upgrade using this type of equipment is critical to a modern CMS in terms of providing state-of-the-art performance. However, its insertion within a military environment presents significant challenges for the military system designer. From an EMI perspective, even though most COTS equipment and systems, by legislation, requires commercial EMI certifications prior to sale, these certifications are based on commercial standards which are not necessarily equivalent to military EMI standards, nor are they always entirely based on physical testing, which represents several risks of non-compliance even in areas of "paper" compliance. Therefore, it is critical for the system designer to understand these gaps and determine the associated risks of integration and collocation of COTS technology within this environment.

It is a well-established concept in commercial design and development to use informal EMI measurement techniques to monitor developmental circuit and equipment emissions to gauge areas of concern for emissions and even susceptibility (or immunity to emissions). This kind of monitoring is called pre-compliance testing as it is informal and takes place prior to formal commercial qualification testing at a certified EMI test house as in Figure 1.4 (Tektronix 2016). These formal tests normally take a long time and attract very high fees. Hence, the use of pre-compliance testing to give confidence of a first-time pass. A failure would require rework, delays to market and other commercially unpalatable impacts.

Figure 1.3: A typical piece of COTS ICT, an Ethernet switch/router (CISCO.com)

In the defence industry, there has been a trend to just assume (many times incorrectly) that COTS EMI certifications are somewhat close to military EMI standards and that, in most cases, qualification failures or "outages" are usually relatively minor in nature and can be waived (Dhingra & Nara 2006). This has been historically acceptable by the military as the military standards were all but obsolete, focusing on limits and frequencies that were no longer areas of concern for modern equipment. However, these standards continue to be updated and as new platforms replace the old, the latest standards are deemed applicable.

There is a very fundamental difference between the focus of military and commercial EMI standards. Military standards are written to control compliance of closely collocated equipment. This equipment may well emit EMI and couple within the near-field to other collocated equipment. It may also closely share power circuits and conducted emissions with that equipment across a broad range of frequencies. However, this entire system of equipment must work together to achieve the critical mission objectives. The commercial EMI standards are very much based on far-field performance and are very focused on controlling levels of interference with television and radio broadcast reception. Commercial radiated emissions standards are only concerned emissions components from essentially beyond the HF band, while military EMI standards have requirements starting as low as 10 Hz. Therefore, there are potentially wide gaps in EMI certifications and qualifications between commercial and military applications (DoD 2001).

It is potentially foolish to consider the historical means of waiving any outages away as an acceptable way forward for the future. As with formal commercial EMI qualification testing, formal military EMI qualification testing is also very expensive and requires several weeks' of effort. A failure or non-compliance may require rework and retesting which could adversely impact budget and schedule. The use of pre-qualification testing to military standards could also benefit development of military solutions which incorporate COTS ICT equipment.

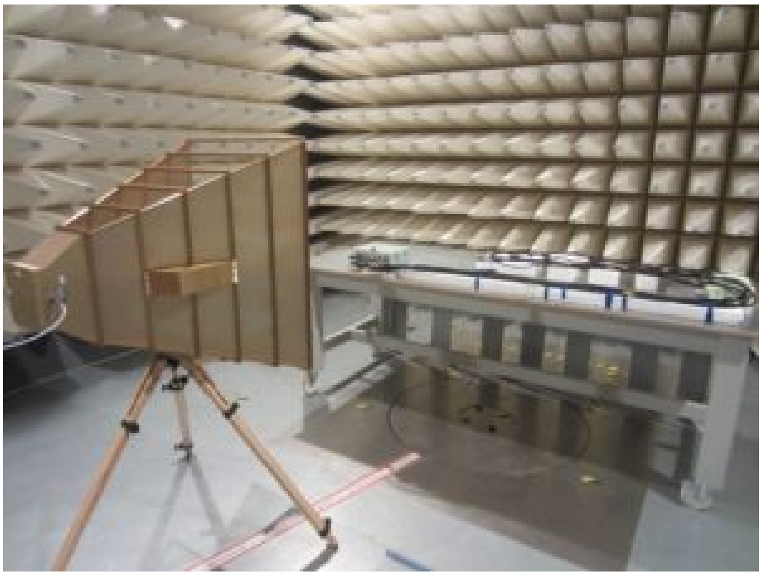


Figure 1.4: A typical military standard Radiated Emissions test setup in a semi-anechoic chamber (Austest.com)

1.3 Aims

The ultimate aim of this work is to fulfil the Programme requirements of the Project Specification of Appendix A. The detailed objectives in Section 1.4 will address these requirements more specifically. Section 1.5 traces the specific chapters of this document to Project Specification Programme requirements points to provide guidance and clarification as to the fulfilment of all necessary Specification requirements.

The intended outcome of this work is twofold. Firstly, it is to confirm the level of compliance of COTS EMI certifications and their underlying commercial standards to the applicable military EMI standard. Secondly, to provide the system designer or Other Equipment Manufacturer (OEM) with a low-cost, readily available means to determine areas on which to focus any remedial efforts to limit COTS EMI emissions.

The intended benefits of these outcomes will permit the designer (or OEM) to realise a compliant system, limiting potential system-level acceptance and qualification test failures, expensive rework and schedule impacts.

1.4 Detailed objectives

With reference to the Project Specification at Appendix A, some of the activities of this project are based on research to explain the historical background and key elements of EMI theory and design, which then leads to the reasoning and motivation for COTS equipment insertion into a submarine combat system.

This then leads to the main objectives of the project, the understanding of the main problem area of non-compliance (or compliance gap) between commercial and military EMI standards and the development of low-investment techniques to collect EMI performance data to help close these compliance gaps for specific COTS ICT equipment.

1.4.1 Gap analysis

The analysis of the compliance gaps between various typical commercial EMI standards against an appropriate military EMI standard in order to determine the risk of EMI non-compliance. Some criteria for comparison will be the respective frequency ranges, EMI emissions limits, measurement distance and associated qualification tests.

1.4.2 Pre-compliance techniques for a military EMI standard

Formally accredited military standard EMI tests are based on prescribed and traceably calibrated test equipment within shielded facilities to provide near ideal circumstances for certified EMI measurements. Pre-compliance testing does not require a near ideal configuration to discover emissions of concern and can be based on a simplified approximation of the relevant military EMI test specification and may be undertaken in a normal laboratory environment.

With the aim of providing a practical alternative to formal qualification testing, another objective of this project is the determination of reduced-cost and practical military EMI emissions pre-compliance testing protocols which can be applied to COTS equipment. This will include the development of simplified, feasible, and relatively easily implemented, radiated and conducted emissions test alternatives, allowing the collection of reasonably accurate COTS EMI performance data to positively determine compliance or areas of concern for the system designer.

1.4.3 Development and experimentation

This will include the design, selection, procurement and development of low-cost sensors, test equipment and various other items and materials required to implement the pre-compliance test configurations and protocols. There will also be a requirement to formulate a means to calibrate and verify the correct operation of the newly developed test equipment items.

The scope of experimentation was extended to include the experimental EMI pre-compliance testing , using the above protocols, of various items of a piece of typical COTS ICT equipment. This level of testing was taken from the list of potential extra work tasks in order to better verify the viability of the developed test protocols.

1.4.4 Extra work if time and resources permit

As stated in Section 1.4.3, some scope was taken from the originally specified *As time and resources permit* section of the Project Specification, leaving these two potential expansion tasks as Extra Work:

- Undertake experimental testing beyond 1 GHz.
- Compare experimental results with certified laboratory test results.

1.5 Overview of this Dissertation

The rest of this dissertation is organised as follows and also provides traceability to the Project Specification of Appendix A:

Chapter 2 is a Literature Review which provides an historical background to the interest in EMI and the formal setting of standards to control it: the motivations for the insertion of COTS in the military environment; some of the elements of the science of EMI; the practical application and challenges of these ideas to a submarine combat system setting; and the concept of applying pre-compliance testing to reduce risk of EMI compliance of COTS equipment. This chapter, predominantly addresses the following Project Specification objectives:

1. Research elements of EMC design in the military environment (such as in a submarine).
2. Research the motivation for COTS equipment insertion into such a military environment.
3. Determine the subset of electromagnetic interference (EMI) emissions limits and tests as applicable to (non-radio) equipment in such a military environment.

However, it also provides the basis, through its literature review, to support the following chapters, that will expand on various ideas from this chapter.

Chapter 3 discusses the methodology to undertake a gap analysis of the commercial EMI standards' compliance to the specific military requirements pertaining to the submarine environment, which is then elaborated and completed in Chapter 4. As well, this chapter defines the methodology used to select, procure and calibrate various equipment and materials required to undertake military standard pre-compliance EMI testing. This chapter draws on the material researched in Chapter 2 and adds further detailed research specific to the following Project Specification objectives:

4. Research the suitability of COTS equipment in respect to EMC compliance in such a military environment.
5. Determine suitable, reduced-cost and practical EMI pre-compliance testing configurations.

Chapter 4 is a Gap Analysis which identifies the key commercial standards for comparison with the predominant military standard. Detailed identification of corresponding limits and other parameters is developed and in-depth analysis is undertaken, using the methodology discussed in Chapter 3, Section 3.2 and fulfils the requirement of Project Specification objective 4.

Chapter 5 shows the design of the necessary facilities and equipment required for pre-compliance testing based on Chapter 3, Section 3.3. This chapter also includes any calibration or verification measurements made to prove the correct operation of these items. This chapter also shows the development of the test sequences for the proposed test protocols, which addresses the requirement of the Project Specification objective:

5. Develop a proposed reference set of simplified, practical and relatively low cost radiated and conducted emissions test protocols which may be applied to COTS equipment with the aim of closing identified relevant military EMC compliance gaps.

Chapter 6 provides evaluation results of trial execution of the protocols developed in Chapter 5. This is accomplished by incorporating the first of the Project Specification objectives identified as being executed only *As time and resources permit*:

1. Experimental testing of these protocols (applying an upper frequency limit of 1GHz) to verify the viability of the proposed tests as a means of identifying EMC design risks.

Chapter 7 provides conclusions inferred from each chapter's research and experimentation, discussing potential changes and suggests further work in the area of practical pre-compliance testing of COTS for the military environment. This chapter will also summarise the fulfilment of the key requirements of the Project Specification.

Chapter 2

Literature Review

This Literature Review encompasses the research and study of the existing body of work defining the theory, concepts, techniques, accepted practices and latest trends supporting the following key tasks of this project.

- The historical developments leading to the motivation for COTS equipment insertion into the military environment,
- Key factors and some of theory behind EMI design in the military environment (specifically in a submarine), and
- The determination of a subset of EMI emissions limits and tests as applicable to equipment in such a military environment.

This chapter also provides the basis for the further discussion and the development of the ideas and methodologies used in later chapters covering the following areas.

- The suitability of COTS equipment in respect to EMI compliance in such a military environment and the determination of any compliance gaps,
- The determination of suitable, reduced-cost and practical EMI pre-compliance testing configurations, and
- The development of a proposed reference set low cost radiated and conducted emissions test protocols which may be applied to COTS equipment with the aim of closing identified relevant military EMI compliance gaps.

2.1 History and Background

As Clayton R. Paul has written in his text "Introduction to electromagnetic compatibility", the first technical papers on the subject of radio interference or what was eventually to be called EMI began to appear in various technical journals around 1920 (Paul 2006). The radio receivers and other equipment such as audio amplifiers of the day were rather crudely designed and suffered from interference either from other nearby equipment or even from internally generated oscillations. EMI from electrical and electromechanical devices such as motors, railway equipment, neon signs and other sparking, arcing and switching machinery began to appear as a major problem around 1930. In 1933 a meeting of the International Electrotechnical Commission (IEC) in Paris recommended the formation of the International Special Committee on Radio Interference (CISPR) in 1934, to deal with the emerging problem of EMI (Jackson 1987, Paul 2006). The committee produced a document detailing measurement equipment for determining potential EMI emissions.

During World War II, the use of electronic devices such as radios, radar, and navigational equipment, such as gyroscopes accelerated at a large rate (Paul 2006). Instances of interference between radios and navigational devices on aircraft began to increase. Originally, these problems were usually corrected by selecting other frequencies on which to operate in a relatively un-crowded spectrum, or physically isolating cables and equipment away from sources of emissions as seen in Figure 2.1 (Javor 2013). It was seen that these simple solutions to correct almost any EMI problem could be implemented on a case by case basis since there was very little and low-density electronic technology at the time, such as vacuum tube electronics.

However, during WWII, there were many instances of mysterious equipment malfunctions, such as that reported by USS Greenling (Trujillo 1995). This account is that of a US submarine making multiple attempts to torpedo a Japanese vessel, each time being thwarted by various mysterious malfunctions, such as the torpedoes either not detonating or detonating too early. While this is not specifically identified as an EMI problem, at the time, there was no means of understanding that the torpedoes did not have an EMI problem as there were no standards or tests to specifically control or understand EMI.

Figure 2.1: - Separation between unshielded antenna lead and the closest adjacent wire bundle on a typical WWII bomber. (https://incompliancemag.com)

In the years following WWII, with the advent of the Cold War, increases in interference problems occurred with the inventions of higher-density electronic equipment (Paul 2006). Major influences affecting increases sources of emissions and susceptible high density electronic equipment was the widespread use of the bipolar transistor in the 1950s, the integrated circuit (IC) in the 1960s and the development of the microprocessor in the 1970s. From the 1980s to the present day, has also seen the frequency spectrum become very crowded with the increased commercial demand for voice, television, radio telephony and general data transmissions.

Figure 2.2: USS Forrestal EMI Incident of 1967 (http://warbirdsnews.com)

One, real-life example of EMI having a catastrophic effect is the U.S.S. Forrestal EMI incident (Leach & Alexander 1995). In this incident, a rocket was spontaneously fired from an armed fighter aircraft on the flight deck of the aircraft carrier USS Forrestal while in action in 1967, off the coast of Vietnam, as seen in Figure 2.2. This rogue missile struck another armed and fuelled aircraft on the Flight Deck, which exploded and caused significant loss of life as well as significant damage and loss of capability for that carrier group, as well as many millions of dollars in financial impact and a not insignificant blow against the US war effort. It was determined that it was the EMI presented by the carrier's RADARs that caused a badly screened weapon control system on an aircraft to signal a false "fire" command.

2.1.1 The advent of military EMI standards

From as early as before World War I (Mazzola 2009), the US military first encountered Radio Frequency Interference (RFI). While very little is known about the earliest efforts to deal with RFI, it appears that various attempts to quantify and control RFI led to definition of the term EMI commencing in the 1930s. Thereafter, a proliferation of various interference and susceptibility specifications were written by the different branches of the military, some of which are listed in Table 2.1.

SPEC. NUMBER	TITLE	TYPE	ERA
MIL-I-6181	Interference Control Requirement	Co-ordinated	06/1950-05/1987
MIL-S-10379	Suppression, Radio Interference, General Requirements, Vehicle	Co-ordinated	07/1951-09/1971
MIL-S-12348	Suppression, Radio Interference, General Requirements for Railway Rolling Stock and Maintenance Way Equipment	Co-ordinated	08/1958-09/1971
MIL-I-43121	Interference Reduction for Electronic Hand Tools	Co-ordinated	12/1962-09/1971
MIL-E-55301	Electromagnetic Compatibility	Army	04/1965-03/1968
MIL-I-16910	Interference measurement, Electromagnetic, Methods and Limits	Navy	08/1954-11/1967
MIL-I-17623	Interference Measurement, Electromagnetic, Methods and Limits For Electric Office Machines, Printing and Lithographic Equipment	Navy	09/1953-12/1967
MIL-STD-826	Interference Control Requirement, Aeronautical Equipment	Air Force	06/1958-01/1962

Table 2.1: US Military EMI specification history - Pre-MIL-STD-461 (Mazzola 2009)

In 1960, the US Department of Defense (DoD) created the "Defense Radio Frequency Compatibility Program", which was later renamed "Electromagnetic Compatibility Program" that concentrated on research and development programs (Mazzola 2009). In 1967, MIL-STD-461 was created along with MIL-STD-462 and MIL-STD-463. It was intended as an EMI specification applicable to all branches of the US military. MIL-STD-461 defined the EMI requirements in terms of limits for conducted and radiated emissions and susceptibility. MIL-STD-462 defined the prescribed measurement methods for qualification testing and MIL-STD-463 provided the prescribed definitions and acronyms. MIL-STD-461G is the current revision of MIL-STD-461, released in 2015; MIL-STD-462D was cancelled and incorporated into MIL-STD-461E in 1999 (EverySpec.com); MIL-STD-463A was superseded by IEEE-C63.14 in 1977, of which the currently active revision is

IEEE-C63.14-2014 (standards.ieee.org).

2.1.2 The advent of commercial EMI standards

At about the same time as the end of the Cold War, in 1991, a revolution was occurring in the computer industry (Guertin & Miller 1998). Driven by the demands of the commercial marketplace and fuelled by the incredibly rapid pace of improvements in integrated circuit technology, computer processing power had increased exponentially. This revolution continues today with computer-enabled digital communications such as 2G, 3G, 4G and 5G cellular telephony and broadband data transmission systems used in various combinations around the globe (Reed, Bernhard & Park 2012). As well, there are free-to-air Digital Television and a host of short to medium range wireless and personal wireless and Internet of Things (IoT) systems (WiFi, Bluetooth, Zigbee, etc). This requires considerable planning with regard to spectrum utilization - Figure 2.3 shows the chronological build-up technologies that have steadily overcrowded the electromagnetic spectrum.

Traditionally, national authorities such as the US Federal Communications Commission (FCC) and what is today called the Australian Communications and Media Authority (ACMA) have been responsible for spectrum management in their respective geographical zones, under the international umbrella of the International Telecommunications Union (ITU). In their earliest embodiments in the radio or wireless age, these organisations were primarily concerned with the control of intentional transmissions and the orderly use of the finite, usable radio spectrum and not specifically the issue of unintentional emitters and EMI.

The CISPR reconvened in London after World War II, in 1946 (Jackson 1987). This meeting was also the first time, delegates from the USA and Canada also attended such an international EMI discussion. The CISPR continues to this day as a special committee of the IEC. Today's European Standards (EN) and IEC commercial EMI standards ultimately call out CISPR limits and testing publications, as does the Australian Standards for commercial EMI.

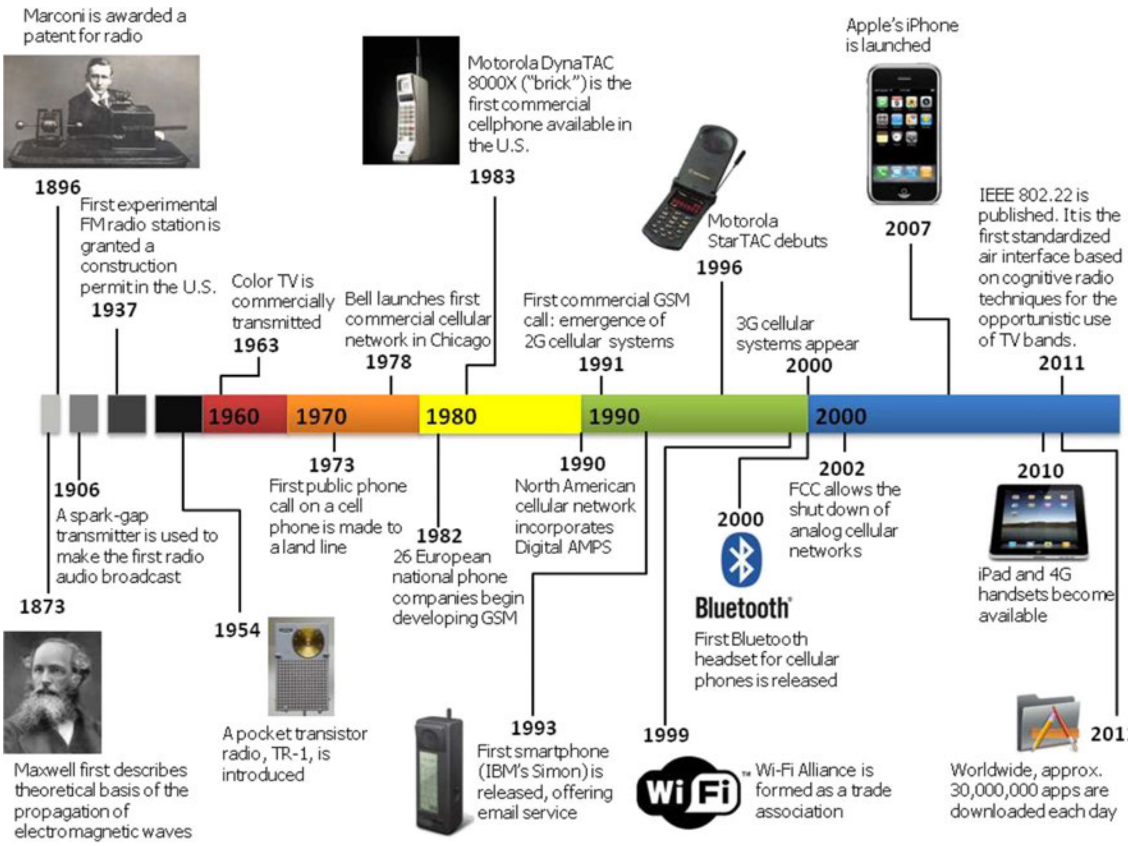


Figure 2.3: A timeline of spectrum access technologies (Reed et al. 2012)

Commercial EMI requirements on more general types of electronics rather than radio communications and broadcast were first introduced in the US by the FCC in 1979 for "computing devices" (understood as the modern term Information Technology Equipment (ITE)) in the Code of Federal Regulations (CFR) 47, Docket 20780 (DoD 2001). The requirements applied today are essentially the same and are limited to conducted emissions on AC power interfaces and radiated emissions only.

Significant controls also occurred in the rest of the commercial world because of the EMC Directive, 89/336/EEC, issued by the European Union in 1996. This directive requires equipment sold in Europe to meet both emission and immunity requirements. The latest update to this directive is 2014/30/EU (EC 2014).

Australia has adopted most of these requirements and has also legislated that equipment sold commercially for use in Australia must meet Australian Standards based on CISPR requirements or an international equivalent under section 162 of the Radiocommunications Act 1992 (www.ACMA.gov.au) (Zombolas 2010). Most other countries have followed suit in a similar fashion as shown in Table 2.2 (Mardiguian, Sweeney & Swanberg 2014).

	Industrial, scientific, and medical (ISM)	Internal combustion engines	Sound and TV broadcast receivers	Household appliances and similar apparatus	Lighting devices including RF	Information technology equipment (ITE)	Automotive, boats, protection of onboard receivers	Cellular telephone systems (mob and base)	Unlicensed RF transmitters (remote ctrl, WiFi, Bluetooth, UWB)
International	CISPR 11	CISPR 12	CISPR 13 (CISPR 32 should soon replace)	CISPR 14	CISPR 15	CISPR 22 (CISPR 32 should soon replace)	CISPR 25		
Australia, New Zealand	AS/NZS CISPR 11	AS/NZS CISPR 12	AS/NZS CISPR 13	AS/NZS CISPR 14	AS/NZS CISPR 15	AS/NZS CISPR 22			AS/NZS 4268
Canada	ICES 001	ICES 002/	BETS-7		ICES 005	ICES 003	CAN/CSA-CISPR 12-10	RSS-118 RSS-129 RSS-132 RSS-139	RSS-210 RSS-310 RSS-220 RSS-GEN
China	GB 4824		GB 13837	GB 4343.1	GB 17743	GB 9254			
European Union	EN 55011	EN 55012	EN 55013 (see CISPR 32)	EN 55014	EN 55015	EN 55022 (see CISPR 32)	Auto Dir. 2004/ 104/EC	ETSI Standards	ETSI Standards
Japan	JIS C 1806-1					VCCI			Japan Radio Regulatory Commission Regulations
Korea	KN 11		KN 13	KN 14-1	KN 15	KN 22			
Taiwan	CNS 13803		CNS 13439	CNS 13783-1	CNS 14115	CNS 13438			
USA	FCC Part 18		FCC Part 15	(Some) FCC Part 15	FCC Part 18	FCC Part 15		FCC Part 22, 24	

Table 2.2: Some international commercial EMI Standards (Mardiguian et al. 2014)

2.2 Motivation for COTS equipment insertion

Prior to the collapse of the Iron Curtain and the end of the Cold War, the US, UK and several other significant militaries were well funded to initiate their own technology development and were a key driving force in developing the state-of-the-art in several areas, including that of electronics and computer technology (Kaminski 1996, Guertin & Miller 1998, Paul 2006). With the end of the Cold War, there was not only a reduction of military funding, but also a shift in technology development from being primarily funded by defence customers to being driven by the domestic consumer and commercial customers. This meant that most of the state-of-the-art, especially that of computer technology, was not being developed for the environmental demands of the military, but to the commercial standards as legislated by the various geographical markets.

2.2.1 Post Cold War acquisition reform

As exemplified by the US DoD, without the Soviet Union as a major threat, the overwhelming public and political view was that there was no justification to maintain defence spending to maintain the high state of existing system performance and capability (Guertin & Miller 1998). In order to maintain its capability, the US embraced a philosophy of reform in the acquisition of its defence and other government materials and systems. That is, to buy cheaper, more readily available and more modern technologies more often. The US DoD took a leading role in pre-empting this reform (Barry 1995), as the then Secretary of Defence, Dr. William Perry, directed DoD program managers to start using performance specifications instead of military specifications and standards, which up to that time, were used to exhaustively detail most aspects of defence systems development.

This acquisition reform was formally put into law as the Federal Acquisition Streamlining Act (FASA) in 1994 (Barry 1995). From a defence perspective, this now meant that in order to meet the national security requirements of the post-Cold War world and also to comply with national domestic policy such as the FASA, the US DoD was to procure state-of-the art technology and products rapidly from reliable suppliers who utilize the latest manufacturing and management techniques.

2.2.2 A new paradigm

Since the implementation of FASA, within the example scope of Submarine development, there have been major moves towards COTS technology insertion (Kaminski 1996, Guertin & Miller 1998). These reforms have not only been driven by the reduced military budgets for technology development, but also reforms for the continuous update and upgrade of capability (Kerr et al. 2008). Since the largest costs are driven by new platforms (such as submarines), there is a general shift in defence acquisition paradigm away from the traditional pattern of developing successive generations of platforms towards a new paradigm centred on support, sustainability and the incremental enhancement of existing capabilities from technology insertions.

The underlying philosophy to this paradigm is that technology is inserted as it evolves and develops throughout the complete service life of a product or platform (Kerr et al. 2008). There are basically three tenets that underpin the technology insertion paradigm.

1. Fewer new platforms (reduction in major capital investment);

2. Extended service lives (longer service for major capital investments), and

3. Increased regular upgrades (faster, cheaper technology refreshment and capability increases e.g. COTS insertion).

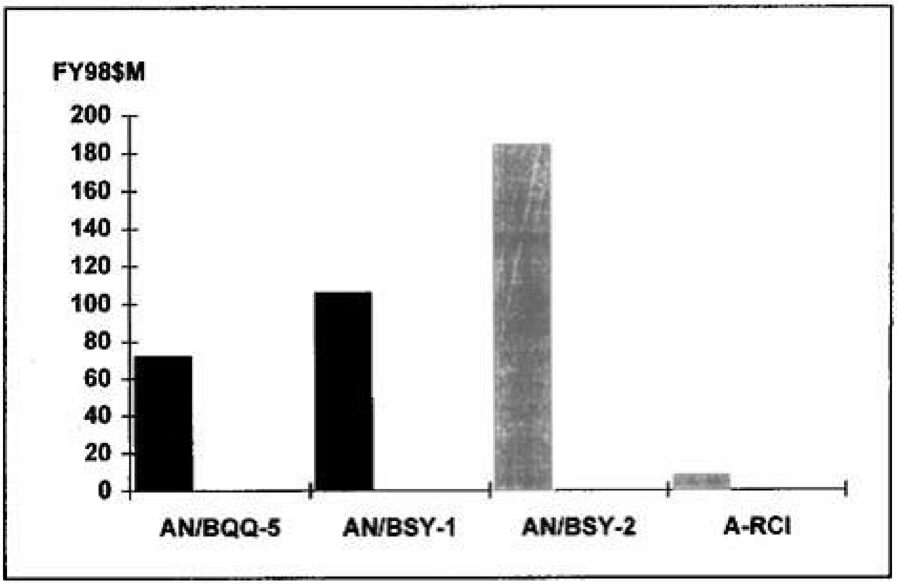


Figure 2.4: Sonar System ship-set upgrade cost comparison between legacy MIL-SPEC systems and the COTS-based A-RCI system (Guertin & Miller 1998)

As exemplified by the Advanced Rapid COTS Insertion (A-RCI) sonar upgrade programme of the US Navy, by using COTS technology, development and acquisition times were substantially shortened (Guertin & Miller 1998). Development times and procurement costs were greatly reduced, as illustrated in Figure 2.4, due to the use of off-the-shelf commercial software and hardware. Although the use of COTS technologies brings with it significant supportability challenges in terms of ruggedisation and sparing, their use has maintained an operational, affordable, and up-to-date sonar system across a large fleet of nuclear submarines, with regularly scheduled application software and hardware improvements. This ensures that the sonar system will be flexible and adaptable to changing Navy requirements and scientific advances.

2.3 Elements of EMI theory and design

2.3.1 The nature of EMI

The cause of an EMI problem may be either within the circuit or system being developed (intra-system) or may be caused by an external system or environment (inter-system)(Keiser 1979). A very common cause of both such problems is that a signal intended for one circuit or system has also reached a system or systems for which it was not intended. A system is said to be electromagnetically compatible with its environment if it (Paul 2006):

1. does not interfere with other systems (inter-system),
2. is not susceptible to emissions from other systems (inter-system), and
3. does not cause interference within itself (intra-system).

Switching transients, signal harmonics and spurious emissions (unwanted artefacts accompanying a wanted signal) may all cause EMI. As seen in Figure 2.5, the "Emitter" is the source of the electromagnetic energy and the "Susceptor" responds to it (Keiser 1979). There are both conducted and radiated transmission paths.

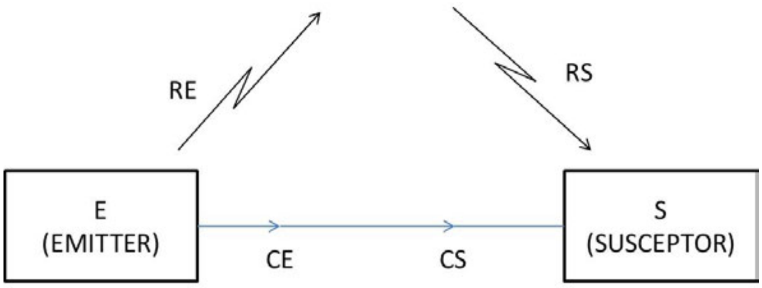


Figure 2.5: Transmission paths (Keiser 1979)

The nomenclature of the associated four basic EMI sub-problems:

1. RE - Radiated Emissions
2. RS - Radiated Susceptibility

3. CE - Conducted Emissions

4. CS - Conducted Susceptibility

"Radiated" emission means that the transmission path was a non-conductive path. The transfer mechanism is by electromagnetic radiation and may be by magnetic field (H-field) or electric field (E-field) coupling, or both. "Conducted" emission means that the transmission path was via one or many conductive elements, such as wires, PCB traces, metallic casings, fasteners or conductive component or effects, which can include real lumped components or stray reactances (Keiser 1979, Paul 2006, Williams 2017).

2.3.2 The nature of electromagnetic radiation

Any conductor which conveys a varying current will radiate an electromagnetic field as a transmitting antenna, unless effectively shielded. Correspondingly, any conductor exposed to such an electromagnetic field will act as a receiving antenna. A conductor can be both a transmitter and a receiver at the same time (Keiser 1979).

Intentional antennas such as AM and FM transmission towers, cellular telephone towers, etc, can generate electromagnetic fields that are meant to couple to appropriate receivers, but can also couple to electronic devices and result in susceptibility problems. In EMI testing, intentional antennas are also used to measure the radiated emissions of a product for determining compliance to the regulatory limits. Unintentional antennas are responsible for producing radiated EMI. Intentional measurement antennas are used to receive or sense this EMI (Paul 2006).

2.3.2.1 An analytical view of radiated emissions

An analysis of intentional antennas can also provide insight into the ability of unintentional antennas to radiate. A convenient manner in which to mathematically model the concept of electromagnetic radiation can be achieved by analysing two key configurations (Keiser 1979, Capps 2001, Mardiguian et al. 2014):

- The field from an infinitesimally small, straight wire, which is sometimes referred to as an Elemental Dipole or a Hertzian Dipole, of length L as shown in Figure 2.6, and

- The field from a magnetic loop antenna of an infinitesimally area A, or an Elemental Magnetic Loop as shown in Figure 2.8.

Figures 2.6 and 2.8 incorporate a spherical coordinate system with coordinates (r, θ, ϕ). The point P is the location of an observation point in free space and is assumed not to be situated close to metallic, dielectric or magnetic medium.

2.3.2.2 Electric field (E-field)

Letting:

ω be the radian frequency $= 2\pi f$,

where f = frequency in hertz,

β be the phase constant $= \dfrac{2\pi}{\lambda}$, where $\lambda = \dfrac{c}{f}$,

(c = 3 x 10^8 m/s, the velocity of light), and

ϵ_0 be the permittivity of free space $= \dfrac{1}{36\pi}$ x 10^9 F/m.

The following Equations 2.1, 2.2 and 2.3 were derived from Maxwell's equations by S.A. Schelkunoff (Schelkunoff 1943), which can be used to resolve most practical cases (Mardiguian et al. 2014). As illustrated by Figure 2.6, it can be shown that the steady-state field, as seen at an observation point P, from a wire of an infinitesimally short length L that carries current I will consist of three components, E_θ , E_r and H_ϕ (Keiser 1979, Capps 2001).

$$E_\theta = \frac{IL\beta^3}{4\pi\omega\epsilon_0}\left[\frac{-1}{j\,(\beta r)} + \frac{1}{j\,(\beta r)^2} + \frac{1}{j\,(\beta r)^3}\right]\sin\theta \tag{2.1}$$

$$E_r = \frac{IL\beta^3}{2\pi\omega\epsilon_0}\left[\frac{1}{(\beta r)^2} + \frac{1}{j\,(\beta r)^3}\right]\cos\theta \tag{2.2}$$

$$H_\phi = \frac{IL\beta^2}{4\pi}\left[\frac{-1}{j\,(\beta r)} + \frac{1}{(\beta r)^2}\right]\sin\theta \tag{2.3}$$

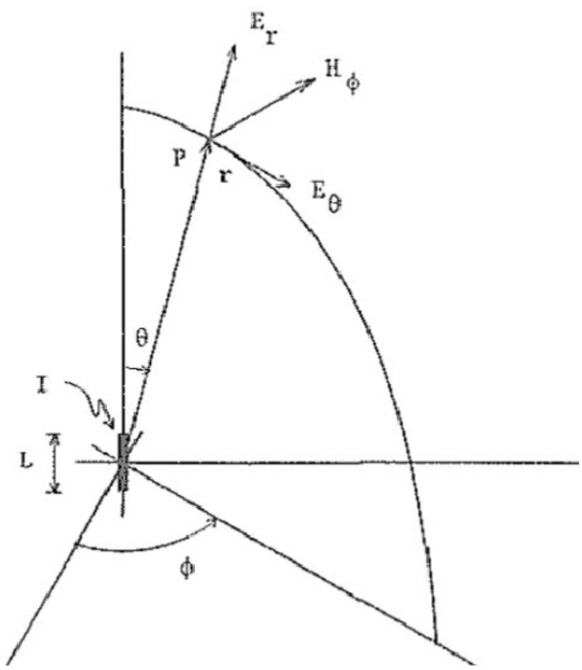


Figure 2.6: Infinitesimally small, straight wire antenna (Herzian dipole) (Keiser 1979)

The conditions for "infinitesimally small" are met while $L << r$ and $L << \lambda$ and if L is short enough that I does not vary along its length (Keiser 1979).

The idea of a uniform current I flowing through a short wire of length L, does not seem to make sense as the current must be zero at the ends of the conductor. However, consider that the conductor may be connected to other conductors of similarly small segment lengths L_n, as illustrated in Figure 2.7.

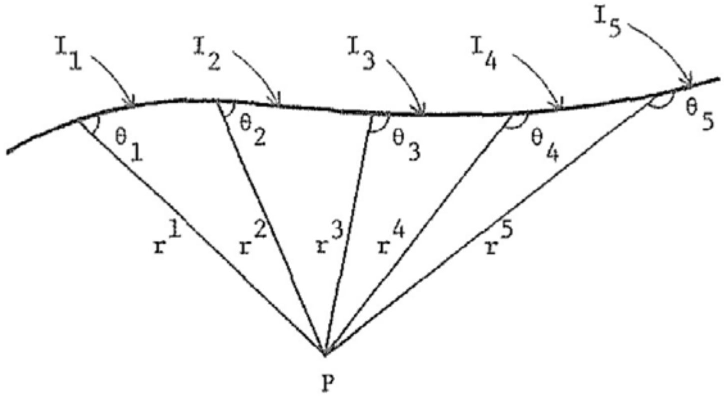


Figure 2.7: Long conductor, segmented into elemental lengths (Keiser 1979)

Each of the segments of length L_n carries the current I_n. However, the field associated with each wire segment observed at the point P, wire will vary as each segment will be at a different distance, r_n, from P. The conditions for which Equations 2.1, 2.2 and 2.3 are valid are met for each segment of the long wire. The total field observed at P will be the (vector) sum of the individual segment fields at distances r_n and angles θ_n.

2.3.2.3 Magnetic field (or H-field)

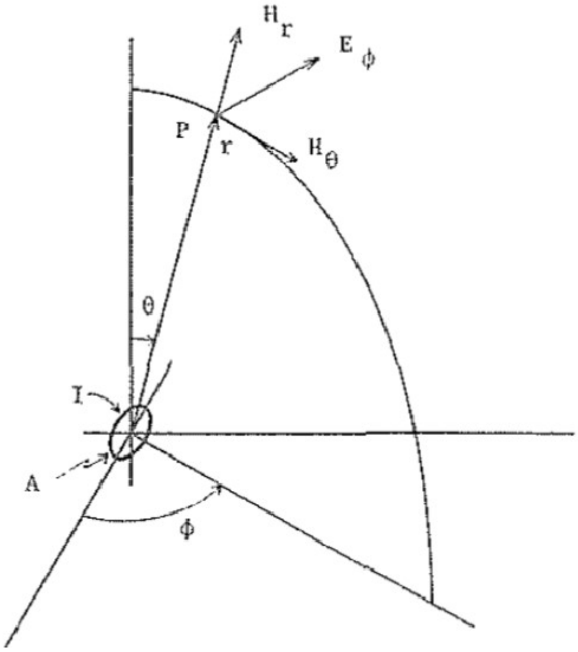


Figure 2.8: Small loop antenna (Keiser 1979)

As shown in Figure 2.8, the field as observed at point P, from a magnetic loop antenna of an infinitesimally area A, which carries current I will consist of three components, H_θ, H_r and E_θ, which are given by the following three Equations 2.4, 2.5 and 2.6 (Keiser 1979, Capps 2001).

$$H_\theta = \frac{IA\beta^3}{4\pi}\left[\frac{-1}{(\beta r)} - \frac{1}{j\,(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\sin\theta \tag{2.4}$$

$$H_r = \frac{IA\beta^3}{2\pi}\left[\frac{-1}{j\,(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\cos\theta \tag{2.5}$$

$$E_\phi = \frac{IA\beta^4}{4\pi\omega\epsilon_0}\left[\frac{-1}{(\beta r)} - \frac{1}{j\,(\beta r)^2}\right]\sin\theta \tag{2.6}$$

To meet the conditions for an infinitesimally small" loop, the diameter of the magnetic loop antenna must be small compared to both r and λ, and I cannot vary around the loop.

Similarly to the example of the Long conductor of Figure 2.7, A large loop can also be segmented into a number of elemental loops, each of area A_n, as illustrated in Figure 2.9, and the fields from each summed vectorially to obtain the total field observed at point P (Keiser 1979).

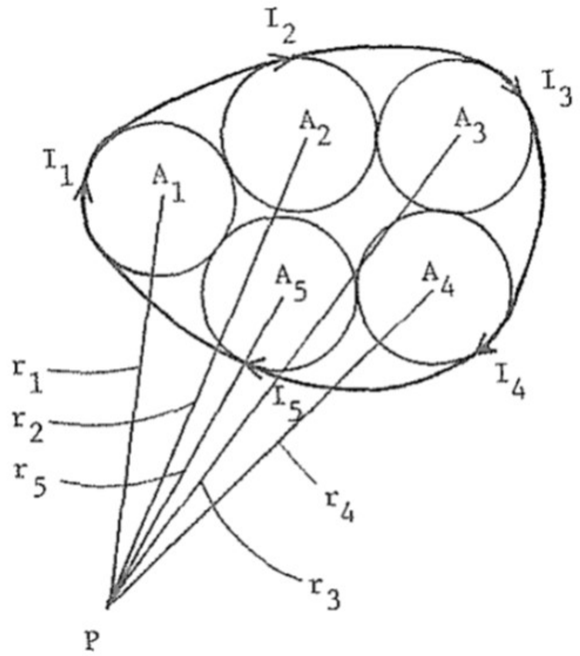


Figure 2.9: Large loop antenna area segmented into elemental areas, A_n (Keiser 1979)

2.3.2.4 The effect of distance from the source of radiation

Equations 2.1 through 2.6 provide expressions for the total field observed at point P regardless of the distance r from the radiation source. However, as the distance, r, becomes large, the $\frac{1}{r}$ terms become dominant and describe what is known as the "radiation" field or "far" field or the Fraunhofer zone (Keiser 1979, Capps 2001, Mardiguian et al. 2014).

According to Keiser (Keiser 1979), as r and becomes smaller, the $\frac{1}{r^2}$ and $\frac{1}{r^2}$ terms become dominant and describe what is known as the "inductive" field or the Transition zone and as r becomes even smaller or as we get ever closer to the source of electromagnetic radiation, the $\frac{1}{r^3}$ terms become predominant and describe what is known as the "static" field or the Fresnel zone (Keiser 1979, Capps 2001, Mardiguian et al. 2014). As can be seen from Equations 2.1 through 2.6, the actual position of the far-field, inductive-field and the static-field (or various other terminology used to describe these zones) is a function of the wavelength, λ, of the electromagnetic radiation of interest.

However, as stated by Capps (Capps 2001), many references refer to only two main zones, the far-field and near-field. To define the boundary between these two zones or fields, a closer examination is needed of Equations 2.1 through 2.6, specifically at the point which the $\frac{1}{r}$ and the $\frac{1}{r^2}$ terms are equal. This is the point where the effect of the $\frac{1}{r^2}$ term wanes and the $\frac{1}{r}$ term begins to dominate the equations. For example, setting the magnitude of these terms in Equation 2.3 equal to one another, the value of r at the boundary between the near-field and the far-field can be found in terms of wavelength (Capps 2001).

$$\frac{1}{(\beta r)} = \frac{1}{(\beta r)^2} \tag{2.7}$$

$$\beta r = 1 \tag{2.8}$$

Expanding the phase constant β, as previously stated, into $\frac{2\pi}{\lambda}$ and rearranging...

$$r = \frac{\lambda}{2\pi} \tag{2.9}$$

Another important concept associated with the transition to the far-field of electromagnetic radiation is that of the wave impedance as illustrated in Figure 2.10. The wave impedance $|Z_w|$ (in Ω), is defined as the ratio of the resultant electric field to the resultant magnetic field at a given point(Keiser 1979). For example, $|Z_w|$ can be found from Equations 2.1 through 2.3, assuming that $r \to \infty$.

Then

$$E_\theta = \frac{IL\beta^2}{j4\pi\omega\epsilon_0 r} \tag{2.10}$$

and, compared to E_θ...

$$E_r \approxeq 0 \tag{2.11}$$

and

$$H_\phi = \frac{IL\beta^2}{j4\pi r} \tag{2.12}$$

Therefore,

$$\begin{aligned}
|Z_w| &= \frac{E_\theta}{H_\phi} = \frac{\beta}{\omega\epsilon_0} = \frac{2}{\omega\lambda\epsilon_0} = \frac{1}{c\epsilon_0} \\
&= \frac{1}{(3\times 10^8 m/s)(\frac{1}{36\pi}\times 10^{-9}F/m)} \\
&= 120\pi(F/s)^{-1} = 377\Omega
\end{aligned} \tag{2.13}$$

It must be stated that the description of near-field and far-field as illustrated in Figure 2.10, is based on the concept of elemental electric and magnetic dipoles with isotropic radiation patterns and will not be identical for other antenna types with more focused directivity (Keiser 1979). While the example does not describe all intentional or unintentional antennas, it does describe the concept of near-field vs far-field, which is of great importance in understanding its criticality to EMI measurement, especially in situations of close proximity between potential radiated emitters and susceptors. In Section 2.3.2.5, below, a more realistic relationship for non-ideal antennas is discussed.

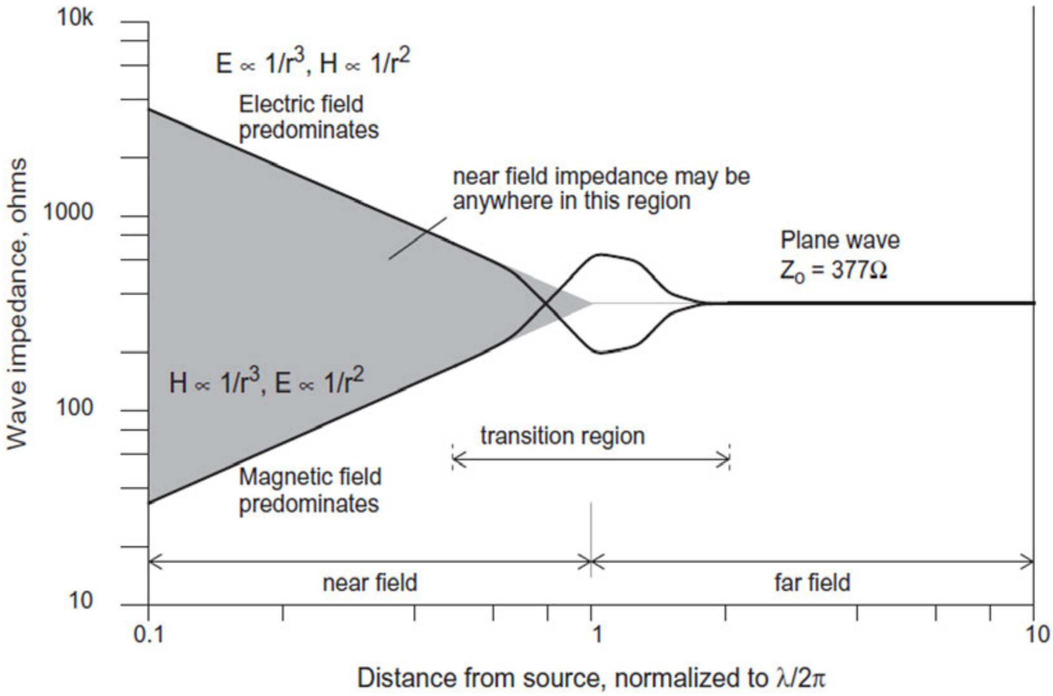


Figure 2.10: Wave impedance of electric and magnetic dipoles based on Maxwell's equations (Williams 2017).

It will be seen, as in Section 2.4.3, that military EMI standards are specifically concerned with the control of EMI in the near-field.

2.3.2.5 Path Loss

As discussed in Section 2.3.2.4, the further away the receiving antenna is from the source of the radiated signal, the lower the energy able to be detected. This can be considered a loss, very similar to the insertion loss of an attenuator. A term for this particular loss is Path Loss (PL), Friis developed a formula known as the Friis transmission formula, Equation 2.14, upon which an expression for PL is developed (Schelkunoff & Friis 1952, Friis 1946).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2} \tag{2.14}$$

Where

P_r is the power in watts received by the receiver antenna,

P_t is the transmitted or radiated power in watts,

G_r is the receiving antenna gain factor (dimensionless),

G_t is the transmitting antenna (or radiation source) gain factor (dimensionless),

λ is the given signal's wavelength in metres, and

r is the distance between the transmitting antenna (or radiation source) and the receiving antenna in metres.

Rearranging Equation 2.14 to define PL

$$PL = \frac{P_r}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi r)^2} \tag{2.15}$$

and, converting to dB for a more practical form

$$PL\,(dB) = G_t\,(dB) + G_r\,(dB) + 20\log\left(\frac{\lambda}{4\pi r}\right) \tag{2.16}$$

It must be noted here that Equations 2.15 and 2.16 are only accurate for circumstances where Equation 2.17, also known as the Rayleigh Criterion is true (Friis 1946, Williams 2017).

$$r \geq \frac{2D^2}{\lambda} \tag{2.17}$$

In terms of radiated emissions measurements, D is the largest linear dimension of the effective aperture of the EUT or the measurement antenna, whichever is greater. If the distance r becomes smaller, the regularity of the emission wavefronts expected in the far-field begin to transition into the less regular shapes of the near-field, which are dependent on the physical geometry of the EUT and antenna.

Frequency	Maximum dimension D (m)	Rayleigh $d = 2D^2/\lambda$ (m)	Maxwell $d = \lambda/2\pi$ (m)
10MHz	1	0.067	4.77
	3	0.6	
30MHz	1	0.2	1.59
	3	0.6	
100MHz	0.3	0.06	0.477
	1	0.67	
	3	6.0	
300MHz	0.3	0.18	0.159
	1	2.0	
1GHz	0.3	0.6	0.0477
	1	6.67	

Table 2.3: Near-field transition zone based on the Rayleigh Criterion compared to that derived from Maxwell's Equations (Williams 2017).

As can be observed in Table 2.3, the smaller the maximum dimension of D, the nearer to the EUT will be the Near-field transition zone.

2.3.3 Sources of radiated emissions

According to Keiser, radiated emissions or interference may be non-functional (or unintentional) as a result of the environment or some nearby unassociated machinery or equipment (Keiser 1979). This may be in the form of lightning or other arc-discharge or similar action, or such as internal signalling, as in the case of high-speed digital logic pulse-trains or power supply switching for example. Radiated emissions may also be functional (intentional), as in TV and Radio broadcast, RADAR or Wifi networking, just to name a few examples.

With respect to example of COTS ICT equipment as used in a Submarine's combat system, intentional radiators are not relevant. Intentionally radiating devices are usually prohibited in such a zone. As well, the fact that the submarine hull is a very effective shield that eliminates such emissions from external sources. Therefore, the focus is on unintentional electromagnetic emissions from collocated equipment. The following is a brief analysis of the most common sources of radiated emissions in such an environment.

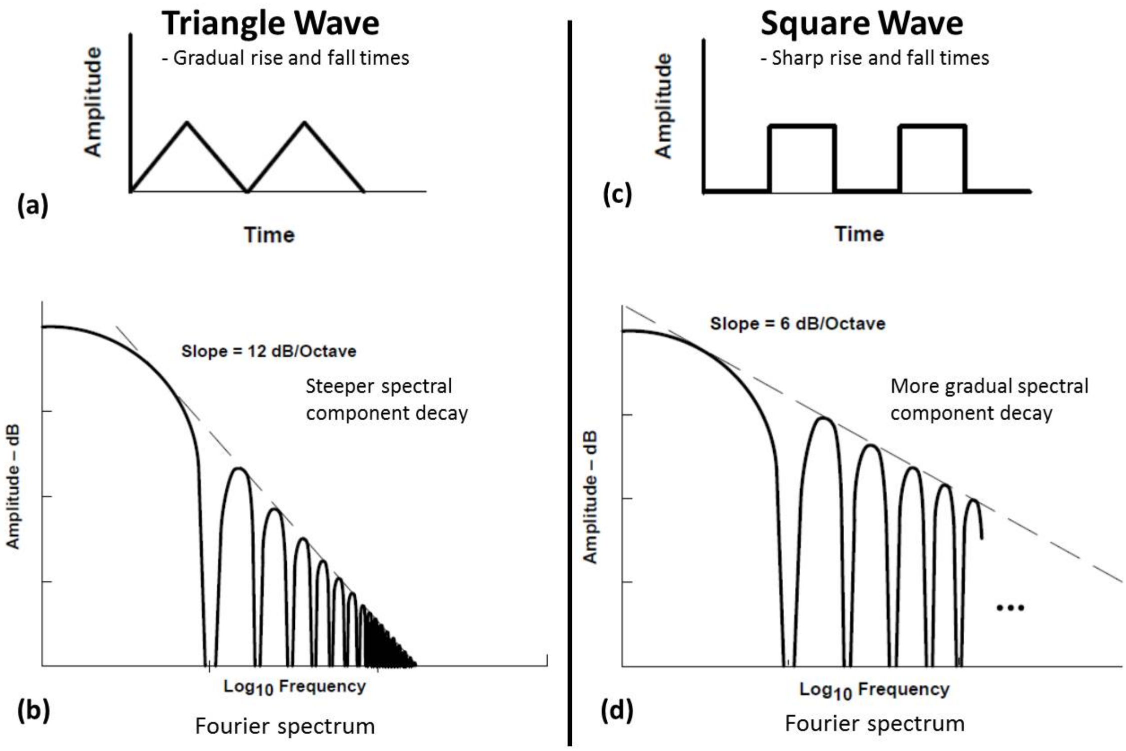


Figure 2.11: Spectral envelope vs rise and fall times (Cho 1994)

2.3.3.1 Spectral content of signals

The frequency content or spectrum of the signals present in an electronic system is potentially the most likely source of radiated EMI from that system (Paul 2006). The higher the frequency of these signals, the more likely they will be to radiate from circuits and equipment. Moreover, the faster the rising and falling edges of such a signal, the more the envelope of its spectral content will extend. The broader the envelope, the greater the potential for radiated EMI.

As illustrated in Figure 2.11, the Fourier spectrum of a signal with relatively slow or gradual rise and fall times will tend to decay quickly, as seen in the case of the triangular wave (a) and its general spectral content (b). In comparison, the ideal square wave of (c) and its much more slowly decaying spectral envelope (d), there is a greater potential for higher frequency components of higher amplitudes to become radiated EMI problems. Even the fastest digital circuitry cannot produce an ideal square wave with rise and fall time of 0 seconds, but the spectrum envelope for a realistic square wave will always be greater than that of a waveform with slewed or more gradual edges and be more likely to cause EMI problems (Cho 1994).

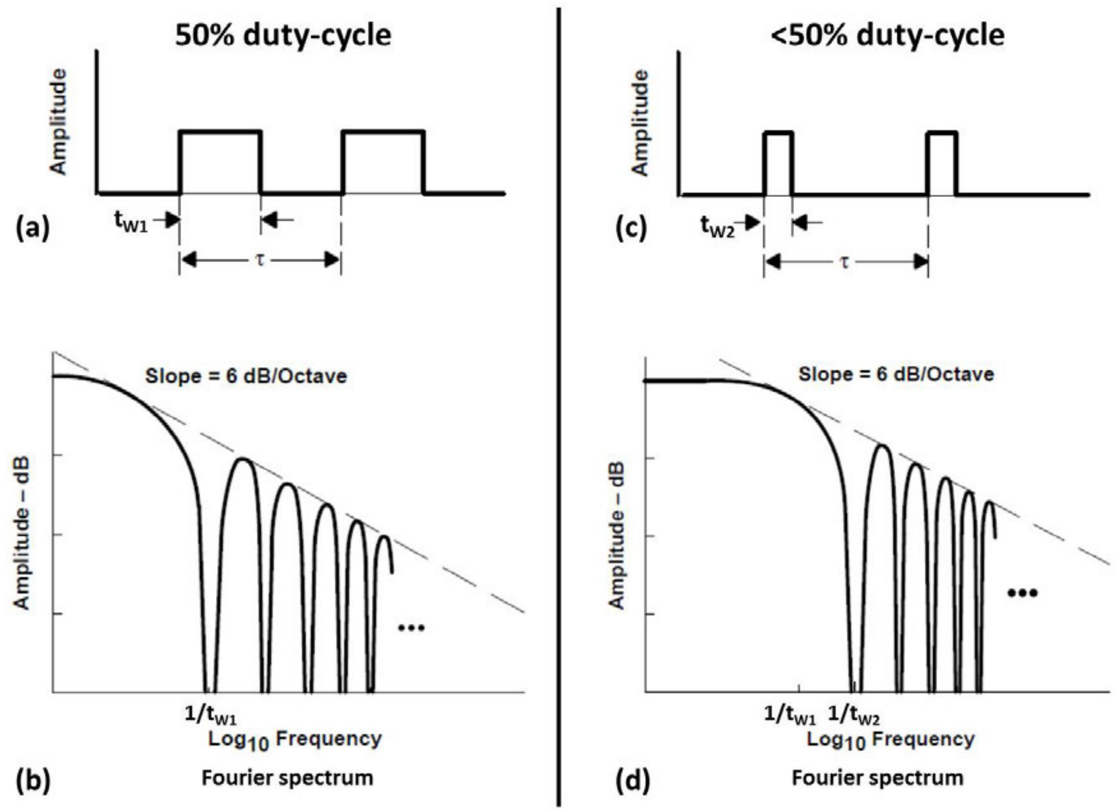


Figure 2.12: Square wave duty-cycle vs spectral envelope (Cho 1994)

As well, the shape of the spectral envelope (or spectral content) of a switching signal such as a digital pulse train, is also affected by pulse duration (or duty-cycle) (Cho 1994, Paul 2006, Mardiguian et al. 2014). Shorter pulse durations equate to frequency spectra exhibiting higher amplitudes at higher frequencies. In comparing Figure 2.12 (a) and (b) (a 50% duty-cycle pulse train or square wave) with (c) and (d) (a <50% duty-cycle pulse train), the following is illustrated. The spectral envelope remains flat up to a frequency equal to the inverse of the pulse duration, or $1/t_{Wn}$. This first node in the frequency plot occurs at a higher frequency $1/t_{W2}$ for the <50% duty-cycle waveform than that $1/t_{W1}$ for the 50% duty-cycle waveform. Beyond this first node in both of the frequency plots, the spectrum envelopes decay at the same rate (Cho 1994).

This shows that:

- the fundamental frequency and its harmonics are a function of the basic time constants of the waveform, and

- the rate of decay of the spectral components is a function of the speed of the rise and fall times of the waveform's edges.

2.3.3.2 Transmission line effects

Transmission of electrical signals between two points occurs over conductors. If those conductors become electrically "long", that is, their length is a at least 1/4 of the signal wavelength, they will take on transmission line characteristics (Cho 1994). If a transmission line is not terminated in its characteristic impedance Zo, some or all of the signal may be reflected back to the source.

While, in practice, signal paths and their returns will likely take a more complex, non-parallel route in many cases, a convenient example for analysis is that of a two parallel conductor transmission line, as illustrated in both Figure 2.13 and Figure 2.14. The reflected signal will superimpose itself on the source or incident signal, resulting in higher or lower amplitudes and potentially higher frequency components being present on the transmission line. This can lead to greater radiated emissions (Cho 1994, Paul 2006).

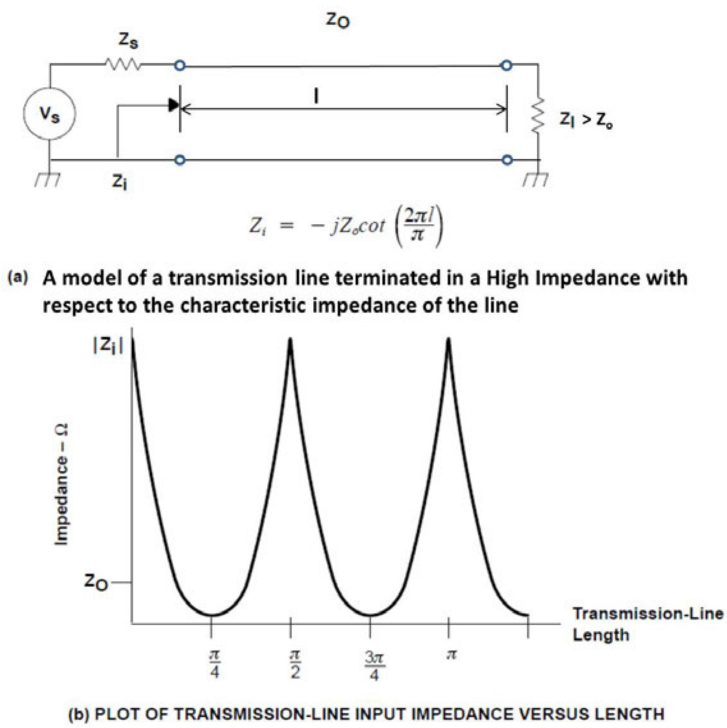


Figure 2.13: Transmission line terminated with an impedance $>Z_o$ (Cho 1994)

Taking further the simplified example of the parallel conductor transmission line shown in Figure 2.13, the termination impedance Z_L is high relative to the transmission-line characteristic impedance Z_O. The transmission-line input impedance versus length can be represented by a cotangent function (Cho 1994).

For a particular signal frequency, the transmission-line input impedance is at a minimum when the transmission-line length is an odd multiple of 1/4 of the wavelength of the signal. When the frequency spectrum of the output waveform of the source Vs, shown in Figure 2.13, contains such frequency components, current through the transmission line and radiated magnetic field emissions from the transmission line are maximized.

Conversely, if the transmission line is terminated with less impedance than the transmission-line characteristic impedance Z_O, as in Figure 2.14, the transmission-line input impedance versus length can be represented by a tangent function. For a particular signal frequency, the transmission-line input impedance is minimized when the transmission-line length is an integer multiple of 1/2 of the wavelength of the signal. When the frequency spectrum of the output waveform of the source Vs, shown in Figure 2.14, contains such frequency components, the voltage or potential on the transmission line is maximised. Radiated electric field emissions are, hence, also maximized at these frequencies.

Therefore, it is imperative to terminate the line in a load matched to the characteristic impedance of the line to avoid reflection and pulse ringing. This would be necessary for the proper functioning of the circuit as well as to curtail a potential EMI radiation issue (Cho 1994, Mardiguian et al. 2014). Unterminated lines will exhibit oscillations that, in addition to possible functional problems, can as much as double emissions levels. When relatively long transmission lines have a high characteristic impedance, they tend to mimic antennae, both receiving and radiating noise easily, so it is desirable to design transmission lines with as low a characteristic impedance as possible (Cho 1994).

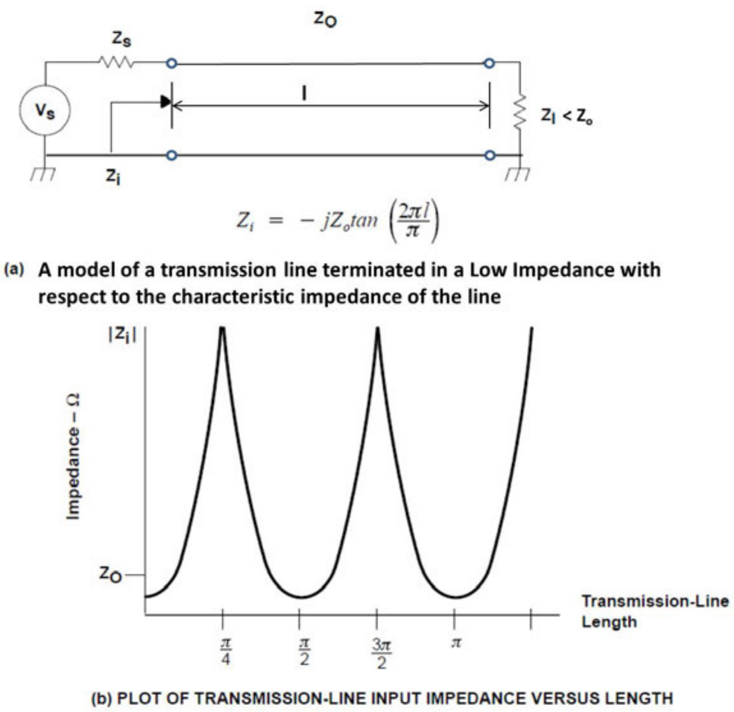


Figure 2.14: Transmission line terminated with an impedance $<Z_o$ (Cho 1994)

In the case of modern ICT equipment, a lot of low frequency content may not radiate efficiently or effectively because the immediate unintentional antennas (internal traces, cables and structures) whose physical length is much less than $\lambda/2$ will not generally match their sources to the surrounding medium (Keiser 1979). Noting that circuit cards, internal chassis, equipment cases and internal cable lengths are likely to be relatively short in length, for example, assuming a worst case of a 1 metre cable carrying a functional signal in an ideal position to radiate, determining $\lambda/2$ indicates that its optimum radiating frequency will be in the order of hundreds of MHz.

However, in much of this equipment, there are lower-frequency circuits, such as in many power supplies, that can develop conducted noise which can couple into nearby cables and equipment cases through stray reactances, which can then radiate (Redl 1996). Figure 2.15 is a more detailed example of the transmission paths (or coupling paths) first illustrated in Figure 2.5. It shows a typical example of the EMI interaction of between collocated equipment (Williams 2017).

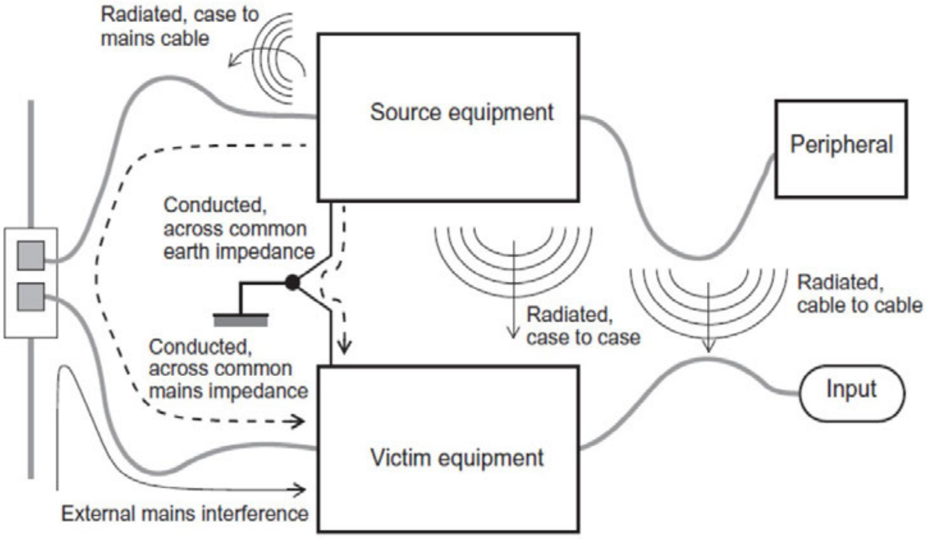


Figure 2.15: Coupling Paths (Williams 2017).

2.3.4 The Nature and Sources of conducted emissions

Conducted emissions are due to the noise currents that are injected into power wiring and conducted out of the product along its power leads. As with radiated emissions, conducted interference may be non-functional, or it may be functional (Keiser 1979).

Non-functional conducted emissions are often associated with electro-mechanical devices such as motor commutators and power switches and relays, by means of arc discharge or by a sudden change in current flow in a conductor (Keiser 1979). However, modern ICT equipment is not likely to be considered to be the sources of these types of non-functional conducted noise.

The most common source of non-functional conducted interference in such equipment will be switchmode power supply input circuits (AC input leads). Their input load currents are very typically chopped and switched in a pulsed manner by semiconductor sampling. Traditionally, switchmode AC-DC converters (or power supplies) use diodes and thyristors to provide controlled DC power. They have typical problems in terms of injected switching current harmonics (Kazem 2007). There are lower-frequency input power rectification related emissions, which are constituted of components related to the AC power frequency and its harmonics. As well, there are higher-frequency power conversion switching noise components generated by converter output stages, which is usually in the tens of kilo

Hertz and higher harmonics, which couple back to the AC input as differential mode EMI through the basic power-conversion process and common-mode conducted EMI through capacitive or inductive coupling (Redl 1996).

Such conducted emissions will almost certainly start within the audio band and will be critical in determining suitability of the equipment under test (EUT) for use aboard a submarine in accordance with military conducted emissions limits, as will be discussed in Section 2.4.3. It should be noted that, as commercial standard conducted emissions limits' lowest frequency of concern start at 150kHz, the lower-frequency power supply emissions of COTS ICT equipment is normally not published or tested and is therefore a potential risk of compliance with military requirements starting as low as the second harmonic of the power line frequency.

Functional interference results when conducted emissions due to the normal functioning of one part of a system directly interferes with the normal functioning of another part or system (Keiser 1979). Such sources of interference are generally easier to address than non-functional sources simply because their frequencies and power levels are generally controlled by the system design.

Examples of functional sources of conducted interference include pulse generators, computer clocks and other periodic generators. In fact, any continuously switching or fixed frequency device is a potential source of continuous wave interference (Keiser 1979).

As with radiated emissions, the waveform is a significant factor in the bandwidth occupancy of the interference (Keiser 1979). In some cases, the designer has control over the waveform and must consider the trade-off between sharp transitions which may be needed to preserve the timing accuracy of an event and smoother, slower transitions with less spectral content. As discussed in Section 2.3.3.1, the sharper the transition (the quicker the rise or fall time), the wider the band occupied. Figure 2.16 shows the normalised bandwidth of various pulse shapes (NAVAIR 1975).

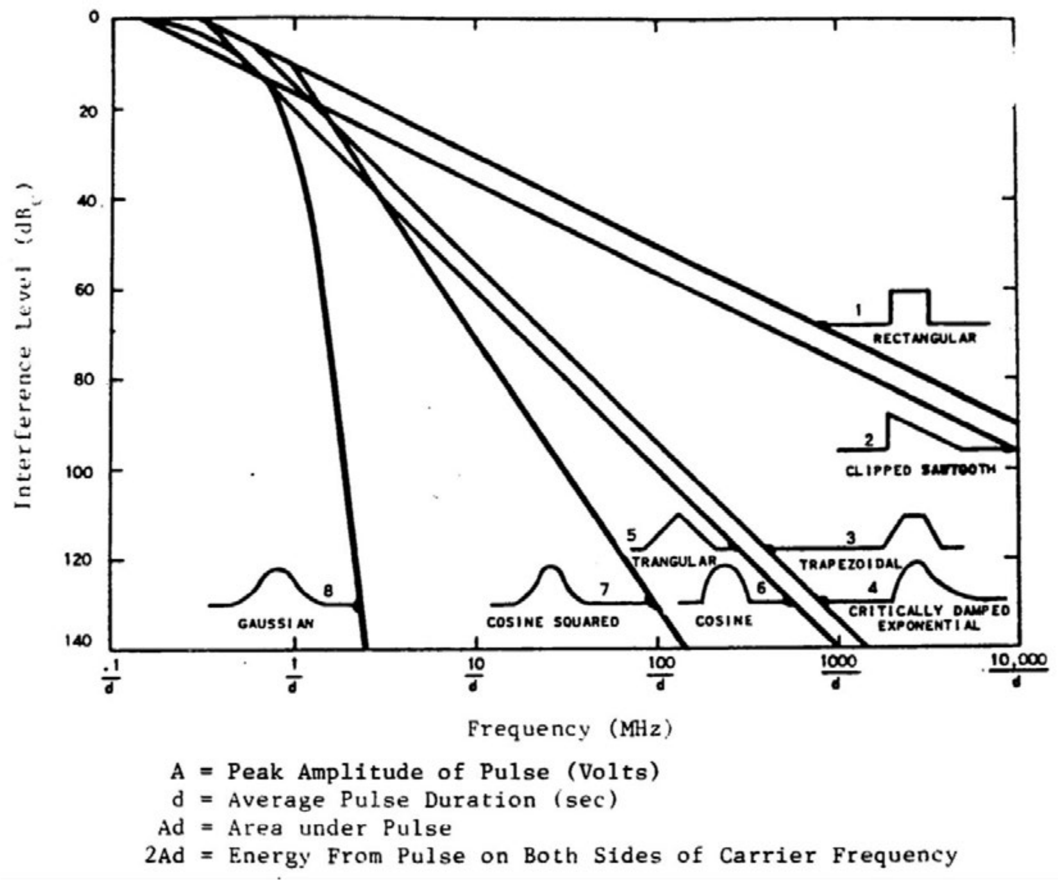


Figure 2.16: Interference bandwidth of various pulse shapes (NAVAIR 1975)

As discussed in Section 2.3.3, the greatest sources of of EMI are due to high frequency components. As graphically summarised in Figure 2.16, lower frequency signals with longer or slower edges are much less likely to cause EMI.

2.3.5 Summary of EMI Design measures

In summary, EMI can be somewhat controlled by design, where possible, via the limiting of potentially threatening signals and good conductor and transmission line layout and design. Some of these design measures are as follows.

- Reducing the frequency of signals where possible
- Reducing rise and fall times of signal switching edges
- Reducing the use of short duty-cycle pulses

- Use impedance controlled transmission line thing and terminate such lines in their characteristic impedance.
- Reduce opportunities of the for inductive or capacitive coupling, such as running long stretches of different signal conductors and power lines bundled together.
- Use of low inductance grounding, allowing better RF grounding effectiveness.

However, in some cases it may be impossible to completely eliminate the presence of such threatening signals, which will require other, protective means to control both conducted and radiated emissions. Some of these measures are listed below.

- Shielding and screening
- Filtering
- Electrical isolation
- Physical separation

2.4 EMI limits, testing standards and the suitability of COTS equipment in a military EMI environment

2.4.1 Commercial versus military EMI standards

As identified by the US DoD, the major differences between military and commercial EMI standards with respect to the example of a submarine application, include the following (US DoD 2001):

1. Requirements in the VLF range for submarines are unique because of critical dependence on the reception of audio band and other low-frequency sonar signals and VLF electromagnetic telecommunications signals. FCC and CISPR requirements typically start at higher frequencies.
2. There is a high concentration of electronic equipment aboard submarines, with multiple equipment and systems required to work in close proximity. For this reason,

military radiated emission limits are more severe than corresponding commercial limits and are specifically concerned with near-field coupling as well far-field coupling.

3. The general availability of grounded conducting surfaces (ground planes) for mounting equipment on a submarine. Most commercial equipment is mounted on an ungrounded table top or floor.

4. Some frequency ranges are more extensive in military standards than they are in commercial EMI standards. As an example, FCC and CISPR radiated emissions limits begin at 30 MHz and up to a maximum of 6 GHz (AS/NZS CISPR 32: 2015), compared to military standards, which begin at 10 kHz and can extend up to 18 GHz.

5. Commercial radiated emissions testing apply a test distance of 3 m to 10 m, compared to the military standard of 1m between the sensor or antenna and the equipment under test (EUT). The short test distance and lower bottom frequency of the military standard includes near field electromagnetic effects, that are not part of typical commercial testing.

These differences preclude commercial EMI certifications from being completely equivalent to military requirements without further investigation. This means that a detailed analysis or further testing is required to determine the adequacy of equipment tested to commercial requirements to meet the requirements of a particular military environment.

2.4.2 Potential Commercial (or COTS) EMI risk areas

2.4.2.1 The focus of commercial EMI standards

The preamble of FCC and CISPR based commercial standards all indicate that the key area of EMI control that they represent is that of limiting equipment emissions in order to provide adequate protection to broadcast services within the residential environment. Further, they classify other equipment which may interfere with broadcast services as not suitable for the residential environment. There is no real treatment of compatibility of equipment to other nearby equipment beyond the effects to broadcast services. The need for multiple equipment and systems to work in close proximity to one another (Dixon 1996, Dixon 1997, Dixon 1998, DoD 2001) and also within potentially hostile EMI environments is not specifically treated in these commercial standards.

2.4.2.2 Electric field emissions only

Many items of COTS equipment have only electric field emission qualifications as in the case of FCC specifications (Dixon 1996, Dixon 1997, Dixon 1998). Under ACMA EMC rules, there are no mandatory immunity requirements (Zombolas 2010). As most imported products or items exported to global markets usually comply with the European CE marking, ACMA accepts the use of any EMI standard (emission aspects only), listed in the European Official Journal of harmonized standards (EC 2014).

2.4.2.3 Non-metallic housings

Many such COTS products utilise non-metallic materials in their housings to reduce both weight and cost. These materials lack appropriate EMI properties that make them risky to use aboard military (Dixon 1996, Dixon 1997, Dixon 1998). They can exhibit:

1. Negligible magnetic field shielding effectiveness,
2. Low and sometimes rapidly deteriorating electric field shielding effectiveness, and
3. Material grounding problems.

2.4.2.4 Potential lack of formal testing

Not all commercially qualified or certified equipment has necessarily been subjected to qualification testing. In the case of the CE Mark (CEMARKING.NET 2018), which is a compliance mark required on all equipment to be sold in Europe and is a common marking on most COTS ICT items. One approach to achieve compliance is a self-declaration where the manufacturer issues a “Declaration of Conformity” that the product complies without third party participation. This is also true for products that claim “verification” to FCC rules (FCC 1996, CEMARKING.NET 2018).

There has been considerable EMI problem experience with COTS equipment insertion in a military environment (Dixon 1996, 1997, 1998; Wilhelm et al. 2005). Since the CE mark or FCC markings indicates that a decision has been made by the manufacturer or importer that the equipment meets the broad intent of the wording of the EMC Directive (US DoD 2001) or FCC rules (FCC 1996, CEMARKING.NET 2018), it does not necessarily indicate what specific tests have been performed or what specific limits have been met. This commercial compliance route represents an extreme risk that such equipment does not necessarily meet any requirements.

Such equipment, provided without proof of third-party certification based on test results, should be specifically re-qualified or at least characterised with respect to MIL-STD-461G to verify its EMI performance prior to consideration for insertion into a military (Dhingra & Nara 2006).

2.4.2.5 General avoidance of early formal testing

In order to reduce costs, projects tend to refrain from individual equipment EMI tests are usually avoided due to formal test lab qualification costs (Dixon 1996, Dixon 1997, Dixon 1998). Typically, most projects save qualification testing for the system level, usually nearing the end of the design cycle. Should there be an EMI test outage or failure, and if the level of the outage is considered minimal or low risk, a waiver is sought from the military or government customer (Dhingra & Nara 2006). If a waiver is not forthcoming, typically expensive rework and usually retesting is then required to remedy the problem and complete the qualification.

2.4.3 MIL-STD-461G application to submarine equipment

2.4.3.1 Applicable subsections of MIL-STD-461G

The predominant military EMI standard for internal submarine applications is MIL-STD-461G (Williams 2017). MIL-STD-461G comprises of eighteen conducted and radiated emissions and susceptibility limits (Table 2.4) and associated test procedures and specific guidance on test equipment and test facility configurations. Also provided is an applicability matrix (Table 2.5), such that only the appropriate limits and tests may be specified for the particular platform, installation or application.

Requirement	Description
CE101	Conducted Emissions, Audio Frequency Currents, Power Leads
CE102	Conducted Emissions, Radio Frequency Potentials, Power Leads
CE106	Conducted Emissions, Antenna Port
CS101	Conducted Susceptibility, Power Leads
CS103	Conducted Susceptibility, Antenna Port, Intermodulation
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation
CS109	Conducted Susceptibility, Structure Current
CS114	Conducted Susceptibility, Bulk Cable Injection
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads
CS117	Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads
CS118	Conducted Susceptibility, Personnel Borne Electrostatic Discharge
RE101	Radiated Emissions, Magnetic Field
RE102	Radiated Emissions, Electric Field
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs
RS101	Radiated Susceptibility, Magnetic Field
RS103	Radiated Susceptibility, Electric Field
RS105	Radiated Susceptibility, Transient Electromagnetic Field

Table 2.4: Emission and Susceptibility Requirements (MIL-STD-461G 2015)

Specific to non-radio, information technology equipment, the Table 2.5 matrix can be used to determine the appropriate requirements for emissions. The following rationale is used:

1. Only the line labelled ‘Submarines’ is applicable;
2. Emissions indicates that only requirements prefixed with CE and RE are applicable, and
3. Emissions requirements indicated as ‘L’, are limited in applicability as elaborated in the body of the standard.

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																		
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS109	CS114	CS115	CS116	CS117	CS118	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	L	S	L	A	S	A	L	S	A	A	L	L	A	L
Submarines	A	A	L	A	S	L	S	L	A	S	L	S	S	A	A	L	L	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S		A	A	A	L	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S		A	A	A	L	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S		A	A	A	L	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S		A	A	A	L			A	L		A	
Ground, Army		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	L
Ground, Air Force		A	L	A	S	S	S		A	A	A		A		A	L		A	

Legend:
A: Applicable
L: Limited as specified in the individual sections of this standard.
S: Procuring activity must specify in procurement documentation.

Table 2.5: Requirements applicability matrix (MIL-STD-461G 2015)

Applying this rationale, the following emissions requirements are found to be potentially applicable from Table 4:

- Conducted Emissions: CE101, CE102 and CE106, and
- Radiated Emissions: RE101, RE102 and RE103.

However, further study of CE106 and RE103 detailed requirements within MIL-STD-461G, shows that these requirements are only applicable to equipment with intentional radio transmitters, receivers and antennas. Therefore, they are not applicable to non-radio IT equipment.

Therefore, the specific emissions requirements of MIL-STD-461G, applicable to submarine combat system non-radio ICT equipment are:

1. CE101 – Conducted Emissions, Audio Frequency Currents, Power Leads
2. CE102 – Conducted Emissions, Radio Frequency Potentials, Power Leads

3. RE101 – Radiated Emissions, Magnetic Field

4. RE102 – Radiated Emissions, Electric Field

Accordingly, the suitability of COTS ICT for insertion in a submarine combat system should be gauged against the above four requirements. Any pre-compliance testing of COTS ICT should seek to measure EMI compliance these requirements. If compliance gaps are discovered, a determination should be made as to what level of risk is represented by those gaps.

2.4.3.2 Submarine power

MIL-STD-461G mandates that the EUT is powered by a controlled supply voltage of the same specification as submarine power and the use of a prescribed filter network to provide a controlled and stable power supply impedance.

A fundamental difference between commercial and military EMI standards is that COTS equipment is assumed to use commercial or domestic AC power supply, as one would find at a general purpose outlet (GPO) with multiple earth neutral (MEN) system (AS/NZS-3000:2018). An MEN system provides that there is an “Active” line and “Neutral” return (for a single phase implementation), which is tied to the ground system. A submarine’s power system and power quality is typically controlled by MIL-STD-1399-300B. This power distribution system, as supplied by the boat’s alternators is 440 V, 60 Hz, 3-phase, 3-wire, *ungrounded* (known as the boat’s primary power). Other voltages are derived from the boat’s primary power by either transformers or static inverters and are all ungrounded systems, which do not have a specific reference to the submarine’s ground system.

2.4.3.3 The Line Impedance Stabilisation Network (LISN)

Emissions measured for verification of compliance with the regulatory limits are to be measured with a line impedance stabilization network (LISN) inserted between the power source and product’s ac power leads (Paul 2006). The AC power cord of the product is plugged into the power output of the LISN. The power input of the LISN is plugged into the power source. AC power passes through the LISN to power the product. In accordance with MIL-STD-461G, the LISN will be constructed as per the schematic in Figure 2.17.

The LISN serves two purposes:

1. It serves as a filter to block external noise present on the AC power supply lines from contaminating the test measurement (Paul 2006). With reference to Figure 2.17, The 50 μH inductor will tend to block noise above the AC line frequency and and the 8 μF capacitor will divert it to ground via the 5 Ω resistor.

2. It serves to provide a stable, reproducible output impedance over frequency, regardless of the impedance presented, looking back into the AC line (Paul 2006). This impedance should be in accordance with the curve shown in Figure 2.18 (MIL-STD-461G 2015). This allows measurements taken at one test facility to correlate with others, regardless of their AC power line impedances.

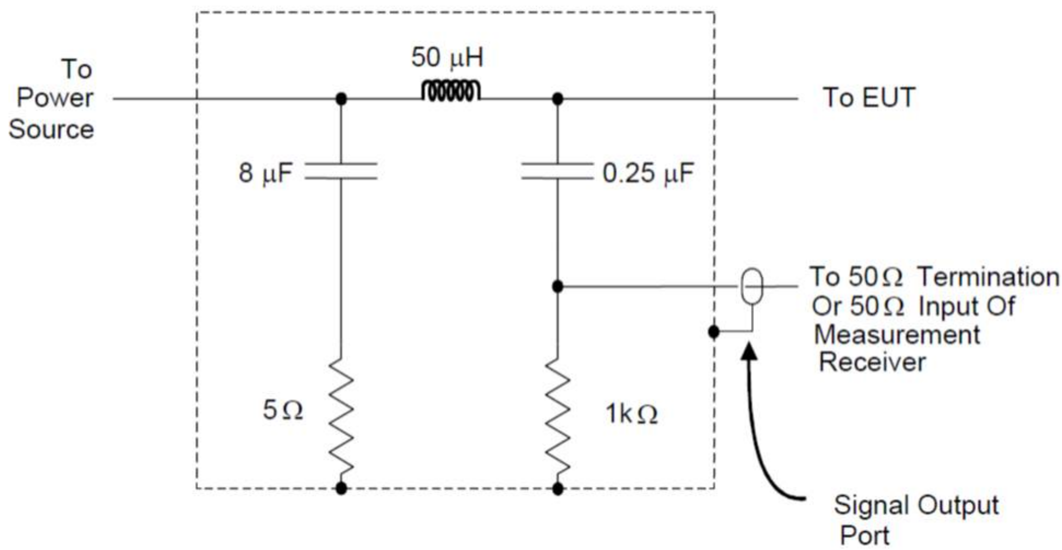


Figure 2.17: LISN schematic (MIL-STD-461G 2015)

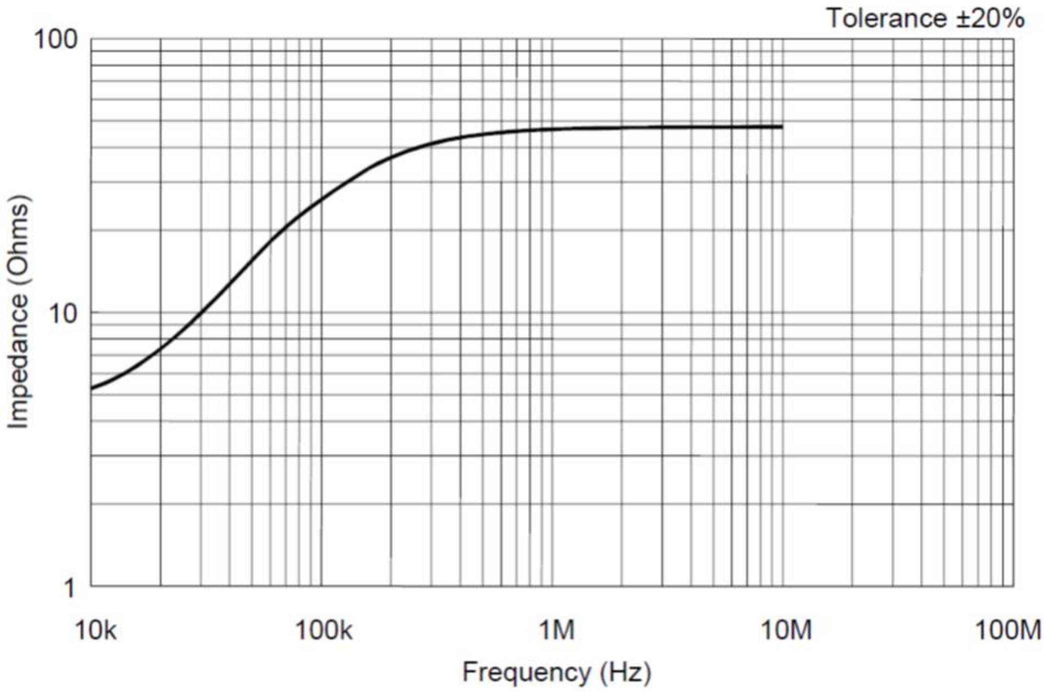


Figure 2.18: LISN output impedance (MIL-STD-461G 2015).

Normally, all measurement procedures of MIL-STD-461G require that the impedance of input power supplies to the EUT will be controlled by LISNs, which will be located at the power source end of the length of the power leads to the EUT. This standard also requires a minimum length of 2 m of power lead between the LISNs and the EUT. The LISNs should have a bond resistance of no more than 2.5 mΩ to the facility ground or local ground plane (MIL-STD-461G 2015).

As a point of note, pre-compliance testing should incorporate such a LISN design to maintain similarity with the formal test configuration. To the same extent, similarity to the rest of the physical test setup guidance should also be maintained as much as possible.

2.4.4 The measurement of conducted emissions in accordance with MIL-STD-461G

As discussed in Section 2.4.3, there are two Conducted Emissions requirements an corresponding tests applicable to the example of a submarine application with non-radio equipment.

1. CE101 – Conducted Emissions, Audio Frequency Currents, Power Leads
2. CE102 – Conducted Emissions, Radio Frequency Potentials, Power Leads

CE101 and CE102 use different test configurations.

2.4.4.1 CE101, conducted emissions, audio frequency currents, power leads

This requirement covers the frequency range is from 30 Hz to 10 kHz for power leads, including returns, as illustrated by Figure 2.20 (MIL-STD-461G 2015). CE101 testing measures audio frequency currents by means of a current transformer, clamped on one power lead at the time as shown in Figure 2.19.

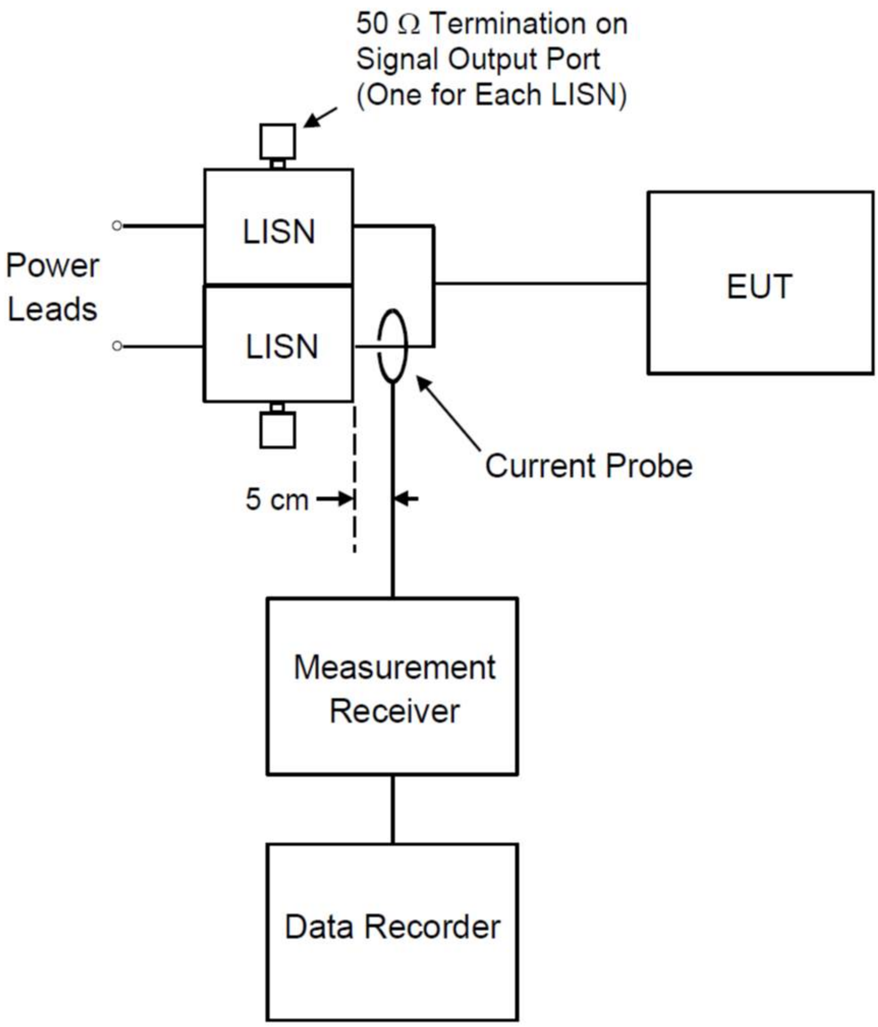


Figure 2.19: CE101 Measurement setup (MIL-STD-461G 2015). Note that the measurement ports of LISNs should be terminated with 50 Ω

For AC applications, this requirement is applicable starting at the second harmonic of the EUT mains supply frequency (MIL-STD-461G 2015). Therefore, since the submarine power system frequency will be 60 Hz, the lowest frequency of test measurement interest will be 120 Hz when the EUT is powered by AC. The CE101 limits stipulate that, for submarines, the conducted emissions limits are not to exceed the applicable values shown in Figure 2.20 for a 60 Hz AC supplied EUT.

For surface ships and submarines, the intent of this requirement is to control the effects of conducted emissions peculiar to the shipboard power distribution system. Harmonic line currents are limited for each electrical load connected to the power distribution system .

Although ship's power distribution is ungrounded, there potentially exists a virtual AC ground at each electrical load due to distributed capacitance to chassis (or the ships metallic structure). The imbalance between the virtual grounds at each electrical load causes AC currents in the hull of the submarine, which can degrade the performance of electronic equipment and upset ground leakage detectors. Therefore, hull currents are controlled by limiting harmonic currents conducted on the power distribution system for each load (MIL-STD-461G 2015).

Of note, there is an allowed "relaxation" (or adjustment) to the CE101 limit line based on the load presented by the EUT, as per the notes in Figure 2.20 (MIL-STD-461G 2015). For example, assuming that the EUT is a device that dissipates a nominal 350 W of 115 VAC power, the following determination of a limit relaxation will apply.

$$dB_{relaxation} = 20 \log 10 \left(\frac{350}{115} \right) = 9.67\ dB \tag{2.18}$$

This "relaxation" is shown applied shown on Figure 2.20 as the bold, dash-dot line.

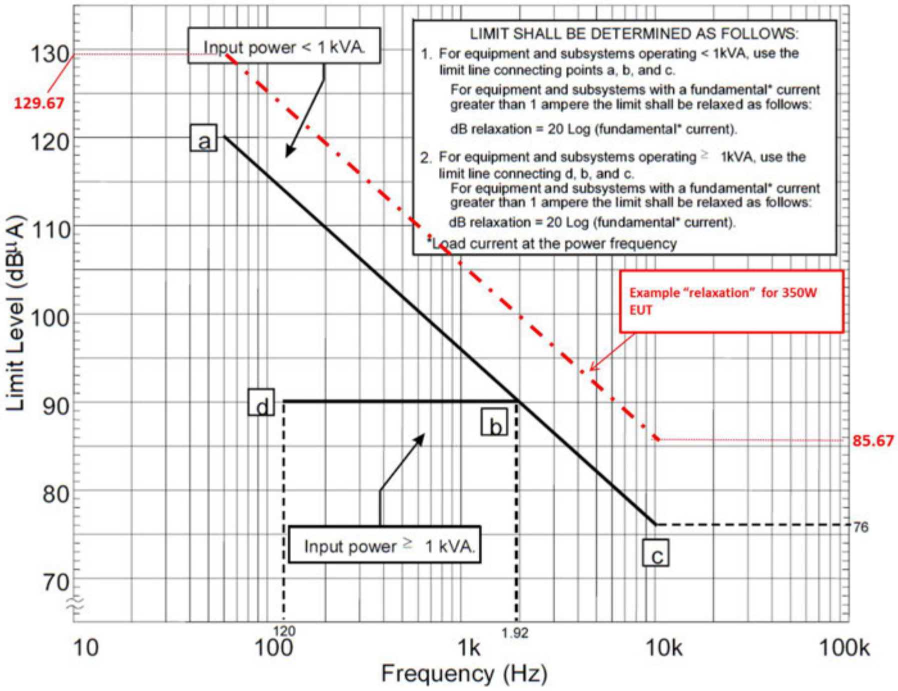


Figure 2.20: CE101 limit for surface ships and submarine applications, AC (MIL-STD-461G 2015). Note the annotations explaining potential "relaxations" or the limit line based on the size of the load presented by the EUT. The dash-dot line shows the "relaxation" of 9.67 dB for the example of an EUT that dissipates 350 W.

A spectrum analyser or EMI receiver usually measures in units of volts or dBμV. The signal from the current clamp will be a voltage developed across the input impedance (usually 50 Ω) of the measuring instrument and is a representation of the current flowing in the power line. To convert the measured units of dBμV into units of dBμA, as per the limits in Figure 2.20, the following conversion is applied.

$$dB\mu A = dB\mu V - 34 \tag{2.19}$$

There is detailed explanation of applicable conversion factors later in Section 3.3.3.

2.4.4.2 CE102, conducted emissions, RF frequency potentials, power leads

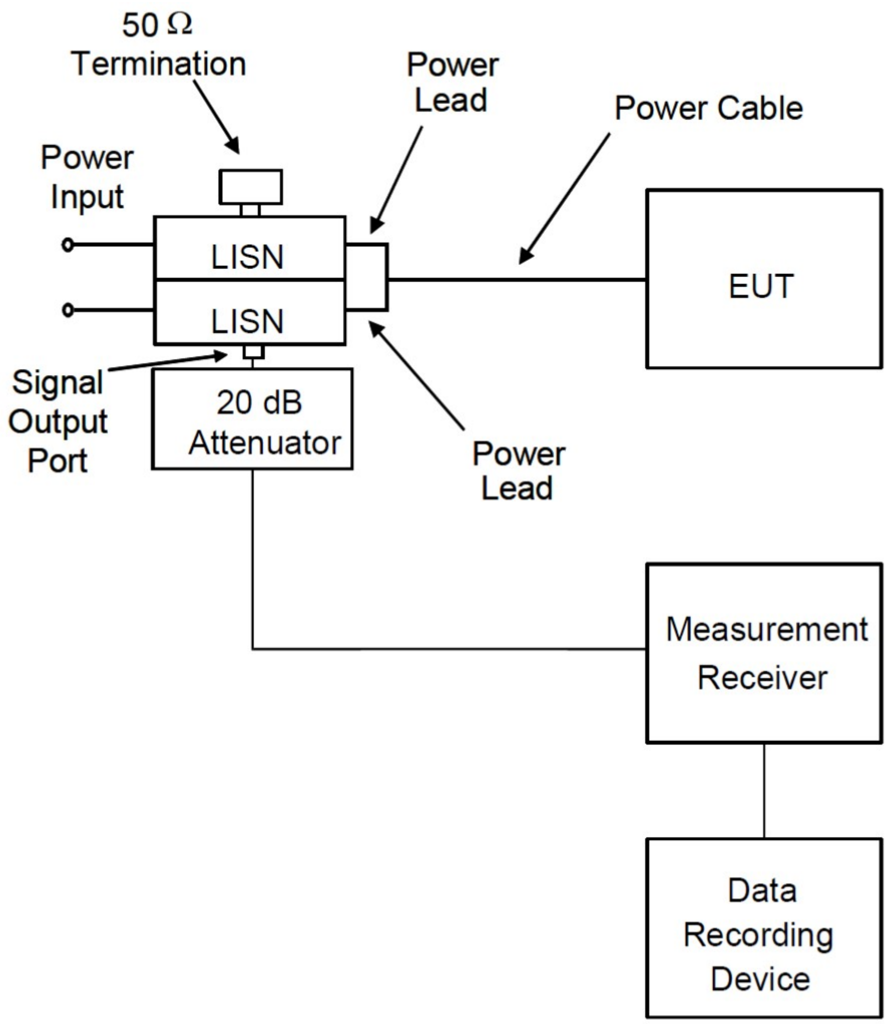


Figure 2.21: CE102 Measurement setup (MIL-STD-461G 2015). Note that the measurement port of the LISN connected to the power line not being measured should be terminated with 50 Ω.

The CE102 requirement covers the frequency range from 10 kHz to 10 MHz for all power leads, including returns, as illustrated by Figure 2.22. CE102 testing measures radio frequency potentials (voltages) directly from the measurement port of the LISN connected on one power lead at the time, as shown in Figure 2.21 (MIL-STD-461G 2015).

The basic concept in the lower frequency portion of CE102 is to ensure that the EUT does not corrupt the power quality (allowable voltage distortion) on the power buses present on the submarine (MIL-STD-461G 2015).

The relaxation for different voltage power sources is based on the relative levels of the power quality curves on ripple for the different operating voltages (MIL-STD-461G 2015).

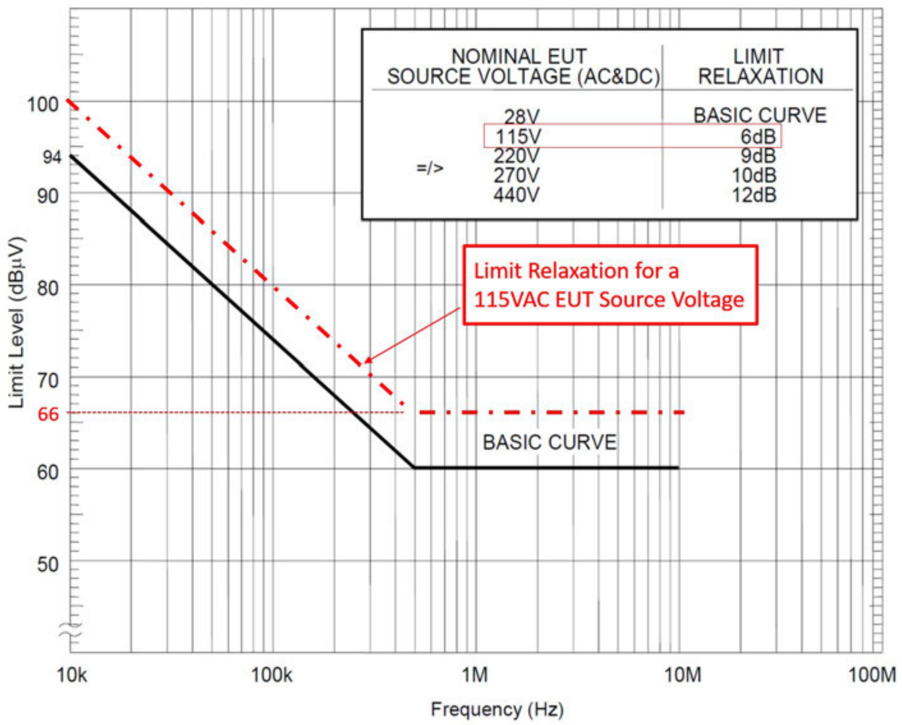


Figure 2.22: CE101 limit for surface ships and submarine applications, AC (MIL-STD-461G 2015). Note the annotations explaining potential "relaxations" for the limit line based on the EUT source voltage. The dash-dot line shows the "relaxation" of 6 dB for the example of an EUT that is powered by a 115 VAC supply.

At higher frequencies, the CE102 limit serves as a separate control from RE102 (radiated E-field emissions) on potential radiation from power leads that may couple into sensitive antenna-connected receivers. The power source impedance control provided by the LISN is a critical element of this test. This control is imposed due to wide variances in characteristics of power line impedances and to provide measurement repeatability (MIL-STD-461G 2015).

2.4.5 The measurement of radiated emissions in accordance with MIL-STD-461G

As discussed in Section 2.4.3, there are two Radiated Emissions tests applicable to the example of a submarine non-radio equipment.

1. RE101 – Radiated Emissions, Magnetic Field
2. RE102 – Radiated Emissions, Electric Field

RE101 and RE102 use different test configurations.

2.4.5.1 RE101, radiated emissions, magnetic field

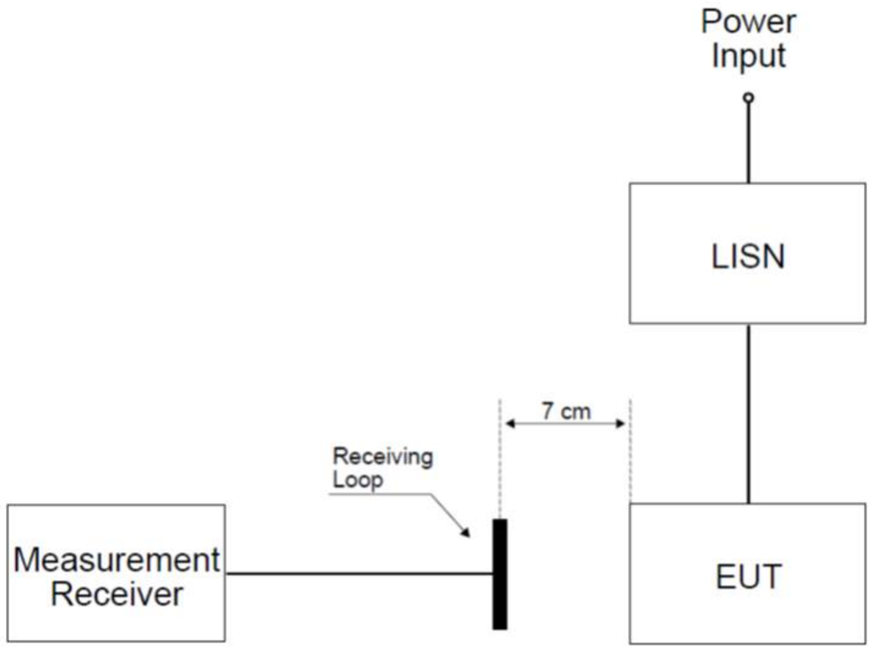


Figure 2.23: Test setup for RE101, magnetic field at a distance of 7 cm (MIL-STD-461G 2015)

RE101 measures radiated magnetic field emissions from equipment and subsystem enclosures, including electrical cable interfaces. The RE101 requirement covers the frequency range from 30 Hz to 100 kHz, as illustrated in Figure 2.24. RE101 testing measures radiated magnetic field emissions from equipment and subsystem enclosures, including electrical cable interfaces (MIL-STD-461G 2015).

The test configuration is based on the use of a magnetic loop sensor (MIL-STD-461G 2015). The sensor loop incorporates an electrostatic shield that prevents detection of electric fields and only develops a voltage across the 50 Ω input load of the measurement receiver, as illustrated in Figure 2.23, proportional to the magnetic field emissions. Measurements are made at a distance of 7 cm from the EUT. The EUT is to be powered through a LISN.

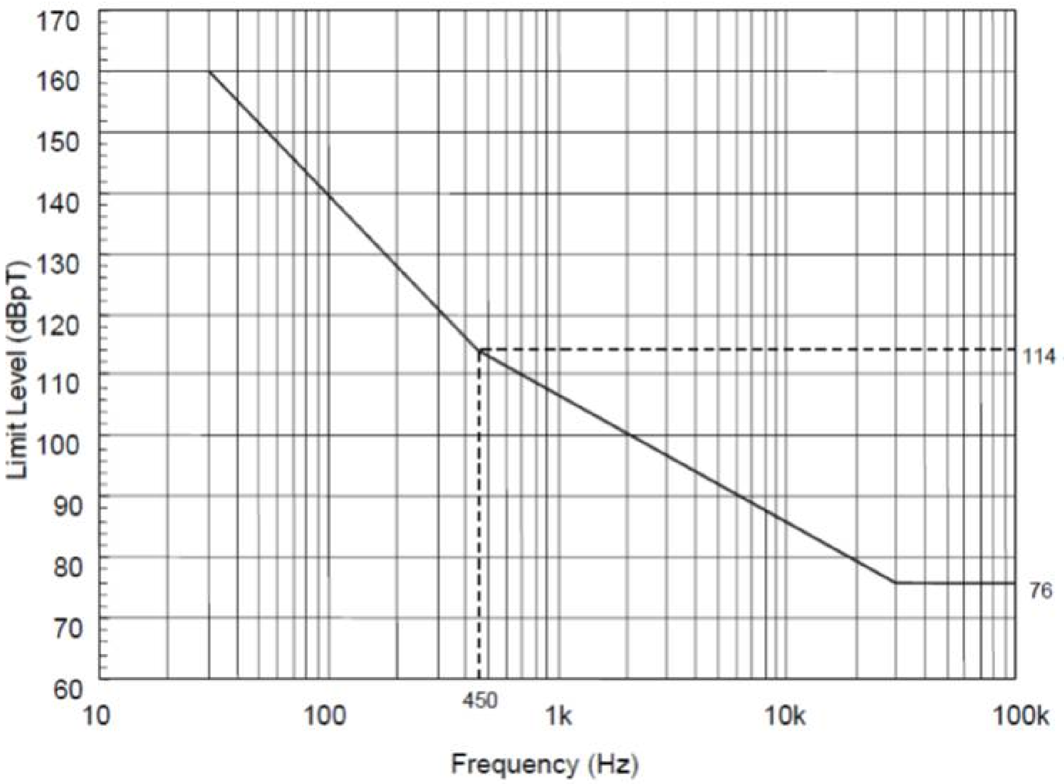


Figure 2.24: RE101 (MIL-STD-461G 2015)

The magnetic loop sensor is calibrated in accordance with SAE ARP958, from which a transfer curve is established giving a relationship in dB$pT/\mu V$ over frequency. The spectrum analyser value is read off in dBμV and is then added to the values on the curve corresponding to the respective frequency, giving a value in dBpT. This can then be compared to the limit line in Figure 2.24 (MIL-STD-461G 2015).

2.4.5.2 RE102, radiated emissions, electric field

RE102 measures radio frequency radiated emissions from equipment and subsystem enclosures, and all interconnecting cables. For submarines, the band of interest is 10 kHz to 18 GHz, the limits of which are detailed in Figure 2.25. Above 30 MHz, these limits are required to be met for both horizontally and vertically polarized fields (MIL-STD-461G 2015).

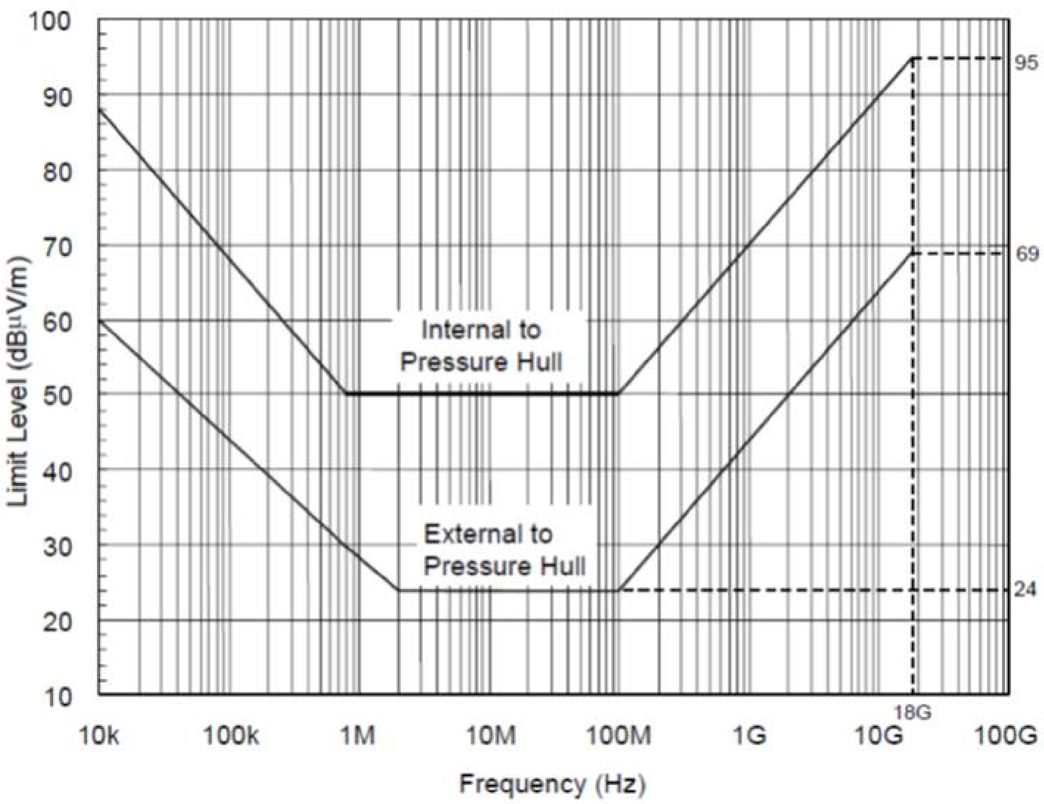


Figure 2.25: RE102 Limits - Submarine (MIL-STD-461G 2015)

The RE102 test configuration is broken into four sections, each requiring a unique antenna arrangement, specific to the respective sub range of frequencies to be measured.

- 104cm Rod antenna 10 kHz - 30 MHz
- Biconical antenna 30 MHz - 200 MHz
- Large dual ridged horn antenna 200 MHz - 1 GHz
- Small dual ridged horn antennas 1 GHz - 18 GHz

For frequencies of 10 kHz to 30 MHz, a 104 cm (41”) Rod Antenna is placed 1 m away (as detailed in Figure 2.26) from the side of the EUT that produces the strongest signal. A measurement is taken in the horizontal polarisation only (MIL-STD-461G 2015).

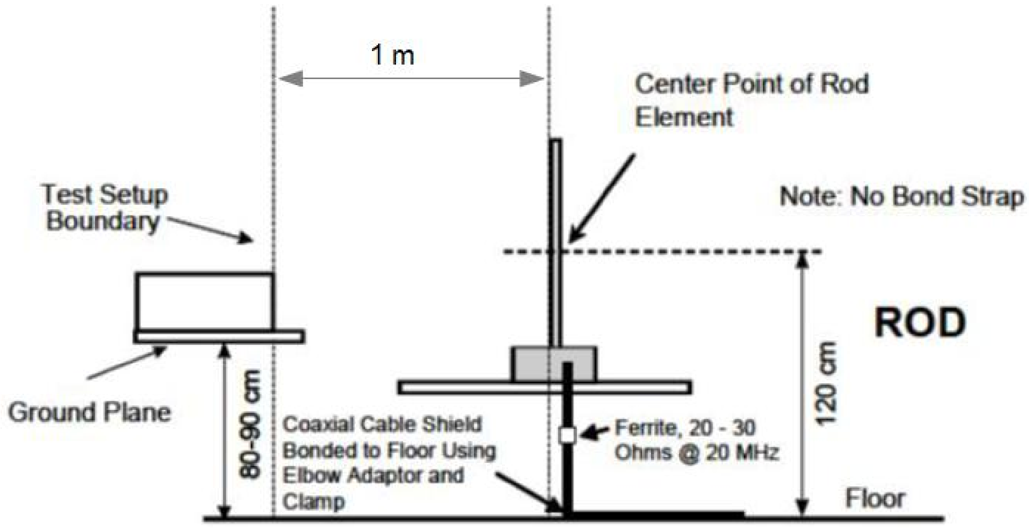


Figure 2.26: RE102 Test Setup - 104 cm Rod Antenna (MIL-STD-461G 2015)

For frequencies of 30 MHz to 20 0MHz, a Biconical Antenna is placed 1m away (as detailed in Figure 2.27) from the side of the EUT that produces the strongest signal. A measurement is taken in the horizontal an vertical polarity (MIL-STD-461G 2015). The Biconical antenna (ANSI 2017, MIL-STD-461A 1968) is sized and constructed as per ANSI C63.5 and detailed in MIL-STD-461A, as illustrated in Figure 2.28.

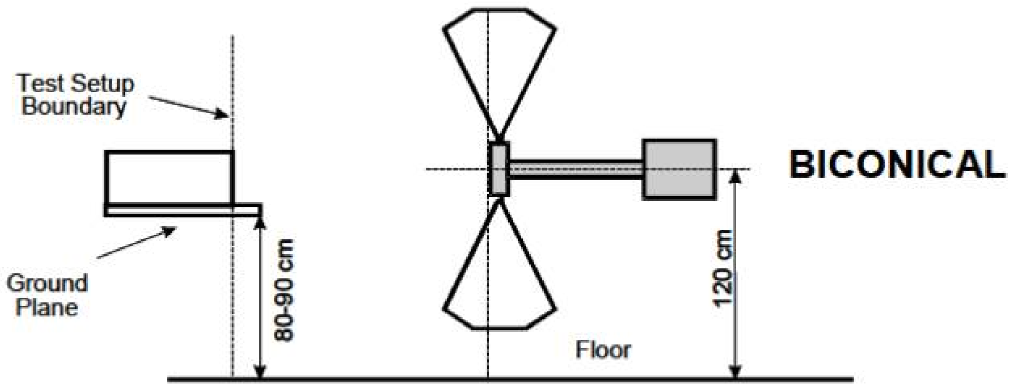
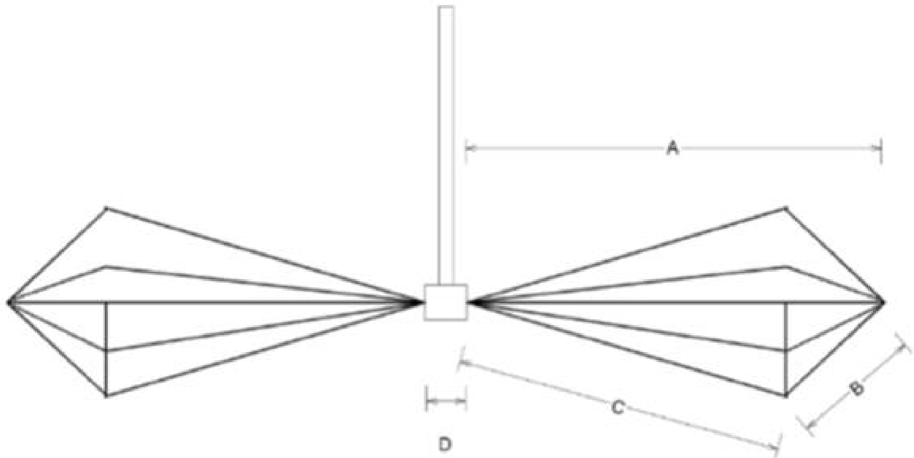


Figure 2.27: RE102 test Setup - Biconical Antenna (MIL-STD-461G 2015)



Dimension	Original MIL STD 461A cm (in)	Minimum cm (in)	Maximum cm (in)
A	60.6 (23-7/8)	60.0 (23-5/8)	64.3 (25-5/16)
B	28.7 (11-5/16)	28.0 (11)	30.0 (11-13/16)
C	50.2 (19-3/4)	52.5 (20-2/3)	54.0 (21-1/4)
D	12.7 (5)	4.0 (1-3/4)	13.0 (5-1/8)

Figure 2.28: Dimensions of biconical dipole antenna as per original MIL-STD-461A (ANSI 2017)

For frequencies from 200 MHz to 1 GHz, a Large Dual Ridged Horn antenna is placed 1m away (as detailed in Figure 2.29) from the side of the EUT that produces the strongest signal. The antenna is to be placed in a sufficient number of positions such that the entire area of the EUT and the first 35 cm of cables and leads interfacing with the EUT are within the 3 dB beam-width of the horn.

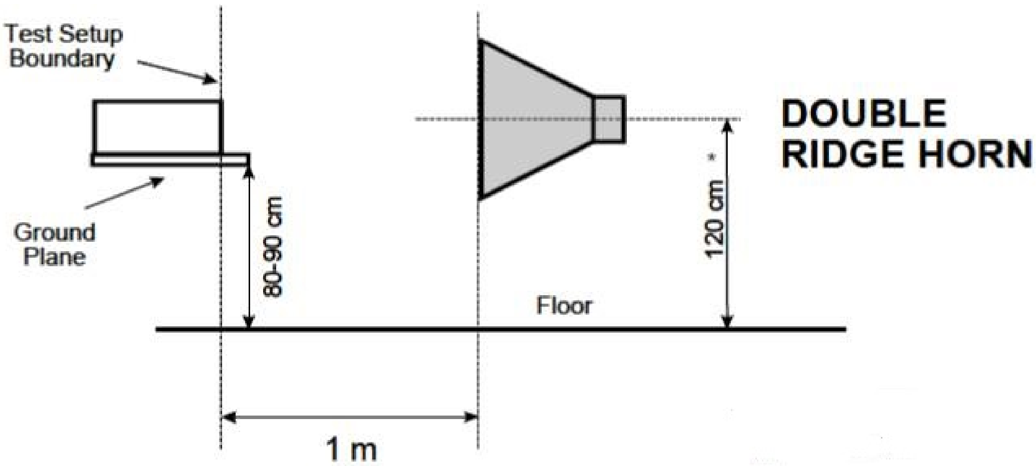


Figure 2.29: RE102 Test Setup - Double-Ridged Horn Antenna (MIL-STD-461G 2015)

From 1 GHz to 18 GHz, a Small Dual Ridged Horn antenna is to be placed in a sufficient number of positions such that the entire area of the EUT and the first 7 cm of cables and leads interfacing with the EUT are within the 3 dB beam-width of the horn (MIL-STD-461G 2015).

2.4.6 Other Key Parameters Associated with MIL-STD-461G

MIL-STD-461G provides reasonably strict guidance with respect to measurement equipment capabilities and settings. Any frequency selective measurement equipment is allowed for performance of the testing as described within the standard provided that its characteristics meet the constraints as specified in the standard (MIL-STD-461G 2015). The intention of this is to ensure that selected equipment is sufficient to demonstrate compliance with the applicable limits.

In this area, MIL-STD-461G refers to another standard ANSI C63.2, *American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz Specifications*, which, in turn, largely refers to another standard CISPR 16.1.1, *Specification for radio disturbance and immunity measuring apparatus and methods, Part 1.1:Radio disturbance and immunity measuring apparatus - Measuring apparatus.* The following is a condensed listing of the key constraints that are applicable to equipment that may be used for simplified testing, such as a spectrum analyser that would be employed for pre-compliance measurements.

- Detector type
- Resolution Bandwidth (RBW)
- Measurement dwell time
- Video Bandwidth (VBW)

MIL-STD-461G states that a peak detector is used for all frequency domain emission measurements. Section 2.5.2 provides a detailed explanation of the Detector and what types exist.

MIL-STD-461G requires that the measuring receiver for testing purposes must have specific settings for Resolution Bandwidth (RBW) over specific measurement bands. Table 2.6 provides measurement band, resolution bandwidth and measurement dwell time.

Measurement dwell time may not be selectable on some spectrum analysers (Tektronix 2016). Section 2.5.2 provides a detailed explanation of RBW.

Frequency Range	6 dB Resolution Bandwidth	Minimum Dwell Time		Minimum Measurement Time Analog-Tuned Measurement Receiver 1/
		Stepped-Tuned Receiver 1/ (Seconds)	FFT Receiver 2/ (Seconds/ Measurement Bandwidth)	
30 Hz - 1 kHz	10 Hz	0.15	1	0.015 sec/Hz
1 kHz - 10 kHz	100 Hz	0.015	1	0.15 sec/kHz
10 kHz - 150 kHz	1 kHz	0.015	1	0.015 sec/kHz
150 kHz - 10 MHz	10 kHz	0.015	1	1.5 sec/MHz
10 MHz - 30 MHz	10 kHz	0.015	0.15	1.5 sec/MHz
30 MHz - 1 GHz	100 kHz	0.015	0.15	0.15 sec/MHz
Above 1 GHz	1 MHz	0.015	0.015	15 sec/GHz

Table 2.6: MIL-STD-461G Bandwidth and measurement time (MIL-STD-461G 2015).

If a controlled video bandwidth (VBW) is available on the measurement receiver or spectrum analyser, MIL-STD-461G states that it shall be set to its greatest value such that it shall not limit the bandwidth of the receiver's response. Section 2.5.2 provides a detailed explanation of VBW.

2.4.7 Summary of MIL-STD-461G Emissions Requirements

Requirement	Units	Sensor	Placement or Distance from EUT	Frequency Range	RBW	VBW	IF Filter (Gaussian) Form Factor	Minimum Dwell Time	Detector	Limits
CE101	dBµA	Current Clamp	5cm from LISN	120Hz-1kHz	10Hz	Off or Max	6dB	0.15 sec	Peak	Fig 2.19
	dBµA	Current Clamp	5cm from LISN	1kHz-10kHz	100Hz	Off or Max	6dB	0.015 sec	Peak	Fig 2.19
CE102	dBµV	LISN	Measurement Port	10kHz-150kHz	1kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.21
	dBµV	LISN	Measurement Port	150kHz-10MHz	10kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.21
RE101	dBpT	Magnetic Loop Sensor	7cm from EUT	30Hz-1kHz	10Hz	Off or Max	6dB	0.15 sec	Peak	Fig 2.23
	dBpT	Magnetic Loop Sensor	7cm from EUT	1kHz-10kHz	100Hz	Off or Max	6dB	0.015 sec	Peak	Fig 2.23
	dBpT	Magnetic Loop Sensor	7cm from EUT	10kHz-100kHz	1kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.23
RE102	dBµV/m	104cm Rod Antenna	1m from EUT	10kHz-150kHz	1kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.24
	dBµV/m	104cm Rod Antenna	1m from EUT	150kHz-30MHz	10kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.24
	dBµV/m	Biconical Antenna	1m from EUT	30MHz-200MHz	100kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.24
	dBµV/m	Large Dual Ridged Horn	1m from EUT	200MHz-1GHz	100kHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.24
	dBµV/m	Small Dual Ridged Horns	1m from EUT	1GHz-18GHz	1MHz	Off or Max	6dB	0.015 sec	Peak	Fig 2.24

Table 2.7: MIL-STD-461G Emission Requirements for Non-Radio ICT Equipment (detailed criteria)

As identified in Sections 2.4.3.1, 2.4.4, 2.4.5, 2.4.6, there are many detailed criteria that define even this relatively small subset of MIL-STD-461G requirements. Table 2.7, summarises the main criteria discussed in these previous sections.

2.5 EMI Pre-Compliance testing techniques

In the commercial world, it is common today to perform pre-compliance measurements during the design and prototyping stages to identify potential EMI issues and address them prior to formal compliance testing (Tektronix 2016, Mardiguian et al. 2014, Wyatt 2016). Pre-compliance testing techniques help to reduce the risk that a developed product will fail the formal EMI compliance testing, leading to expensive delays to production while redesign and retesting is undertaken.

The performance of basic pre-compliance testing can help discover potential outages by allowing the designer to methodically isolate problem areas and apply appropriate corrective measures. These same measurement techniques will allow the designer to compare EMI performance before and after corrective measures and provide evidence for justification of product design change. This holds true for non-commercial design as, for example, in a submarine combat system's hardware design, incorporating COTS equipment.

2.5.1 Pre-compliance techniques

At the early stages of development, design-for-EMC techniques, some of which are discussed in Section 2.3.5, are employed to attempt to minimise EMI emissions. Pre-compliance testing may be used to verify the effectiveness of these measures. Therefore, identifying emissions problems early enough to help develop the design towards a better outcome. In other words, these measurements will allow a designer to have a more complete understanding of the circuit's or system's emissions and allow the designer to incorporate other measures to control such emissions.

Typically, Pre-compliance techniques are centred on the use of a spectrum analyser and various probes, specific to either conducted or radiated emissions. As in Section 2.4.3.3, a LISN of an appropriate type will be required for conducted measurements (Tektronix 2016, Mardiguian et al. 2014). A LISN can be purchased or even constructed based on details published in the various standards, as illustrated in Figure 2.17.

Radiated emissions, especially at the PCB or small equipment module level are very effectively detected and measured using near-field probes, as shown in Figure 2.30 (Tektronix 2016, Mardiguian et al. 2014, Wyatt 2016, Kraz 1995). However, since near-field readings are greatly dependent on the geometry of the source and its properties (as discussed in Section 2.3.2.4), there is no reliable correlation between measurements performed in the near field to those done in the far field, except to say that, in general, the stronger the field near the source, the stronger it will register in the far field.

Figure 2.30: Use of a near-field magnetic probe (tek.com)

Radiated emissions measurements for larger items such as rack-unit servers, switches and routers, becomes less practical due to the larger areas to cover. It is at this size and over that "far-field" techniques, using EMI sensor antennas may be more practical (Tektronix 2016). However, it must be understood that since MIL-STD-461G prescribes a distance of one metre between the EUT and the sensor antenna, up to approximately 50 MHz to 60 MHz, the geometry of the antenna will also play a large part in the kind of readings obtained as it is within the inductive or transition zone of the near field.

The selection of a suitable test site is also most important (Tektronix 2016). It should be as RF quiet as possible. There will be radio and television broadcast signals and various other communications signals from the environment external to the site. When selecting a test site it is best to pick a location that will minimize external signal sources. Rural areas, subterranean floors or basements are potentially excellent sites because they minimize external background signals that might mask the emission levels being measured (Videnka & Svacina 2009). It is a good policy to turn off as many local sources of RF noise as possible, such as that of fluorescent lighting, Wi-Fi hotspots, mobile phones, electric power tools and other potential sources of background interference.

2.5.2 Appropriate Instrument Settings for EMI Measurements

The general purpose spectrum analyser (rather than a typically very expensive, purpose-built EMI receiver) is key to the ability to undertake economical yet comprehensive pre-compliance measurements. In the case of MIL-STD-461G as applied in Section 2.4.3, the spectrum analyser would be required to able to measure frequencies between 30 Hz to 18 GHz in order to cover the entire spectrum of compliance. However, in the case of non-radio COTS ITE, it is likely that most EMI problems will be found in the lower frequencies rather than above the L-band (over approximately 2 GHz). The price of a spectrum analyser is almost exponentially proportional to its bandwidth. It may be more cost effective to use two lower bandwidth instruments to cover the range required.

2.5.2.1 Resolution Bandwidth (RBW)

The bandwidth of a spectrum analyser measurement is defined by a receiver bandwidth shape or a resolution bandwidth (RBW) or measurement filter. The bandwidths used are representative of the perceived threats within the spectrum, and the bandwidths vary with the receive frequency (Tektronix 2016). Figure 2.31 shows the differences in filter shape for 3 dB vs 6 dB filters. Both filter shapes are Gaussian, but their widths are different. The measurement filter bandwidth is specified at some amount of power down from the peak. 6 dB filters are used for most EMI measurements, including MIL-STD-461G, as stated in Section 2.4.6. Most spectrum analysers use 3 dB by default, however, some have selectable filter bandwidths (Tektronix 2016). This setting is important because measurements will differ with filter shape. While the peaks of the signals should be the same level for a given 3 dB or 6‘dB filter, the measured noise would be lower for the same RBW setting with a 6 dB filter as it will only measure a narrower window of noise, illustrated by the blue filter shape in Figure 2.31.

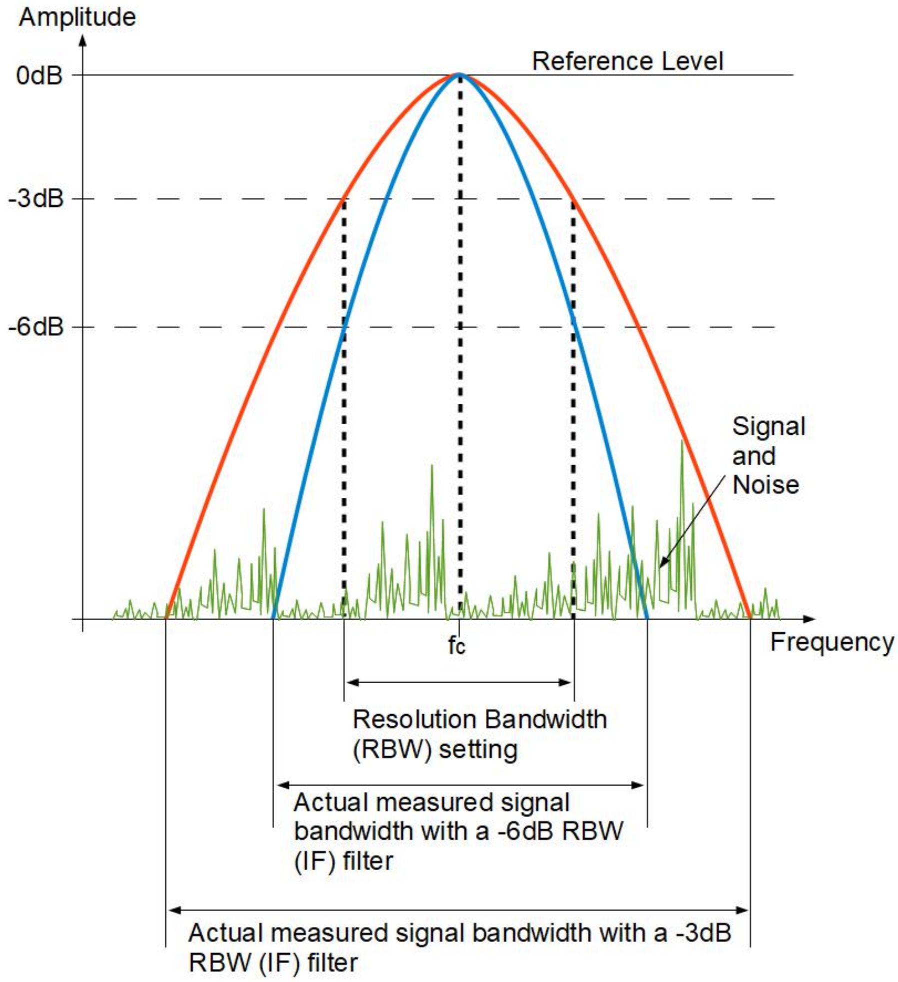


Figure 2.31: Comparison of differences in filter shape for 3 dB (red curve) vs 6 dB (blue curve) RBW filters.

It should be noted that if a spectrum analyser does not provide any other option but a 3 dB RBW filter, it can still be used for pre-compliance testing. However, it will likely provide a higher peak value for any given frequency as more noise bandwidth will also be measured along with the signal of interest. This will tend to provide a "worst case" peak value.

2.5.2.2 Detector Types

A detector calculates a single point that represents the signal over a defined frequency interval. Detection methods can calculate the positive or negative peak, the RMS or average value of voltage, or the Quasi-Peak (QP) value (Williams 2017). Figure 2.32 illustrates and compares their individual characteristics. Commercial standards require the EMI receiver to use quasi-peak (QP) detectors or average detectors for formal compliance tests as their limits are defined correspondingly. Most spectrum analysers will provide a peak and an average detector. As MIL-STD-461G requires a peak detector only, most spectrum analysers will comply with this requirement.

A peak detector responds near-instantaneously to the peak value of the signal and discharges fairly rapidly. If the receiver dwells on a single frequency the peak detector output will follow the "envelope" of the signal, hence it is sometimes called an envelope detector. Its fast response makes it very suitable for diagnostic or "quick-look" tests, even if another detector type is to be used for formal measurements (Williams 2017).

The average detector measures the average value of the signal. For a continuous signal this will be the same as its peak value, but a pulsed or modulated signal will have an average level lower than the peak (Williams 2017).

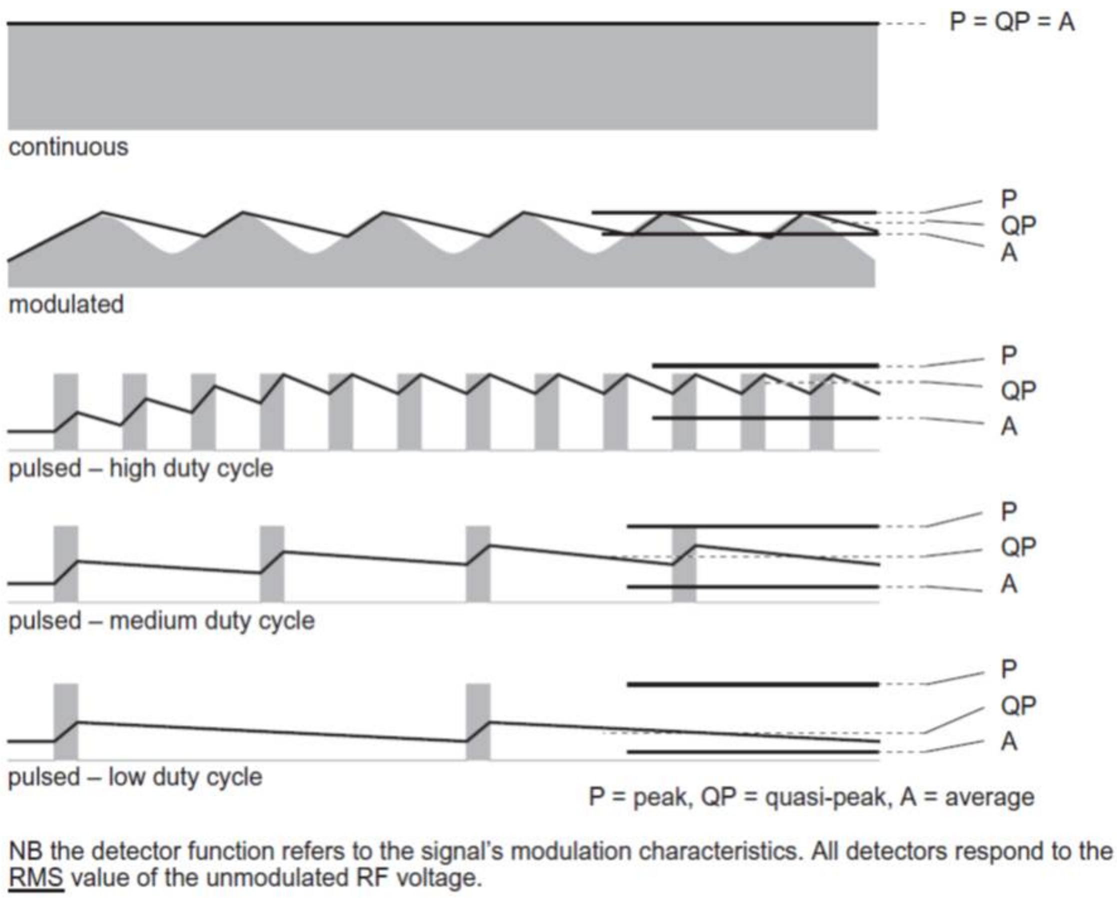


Figure 2.32: Comparison of Peak, Quasi-Peak and Averaging detector types (Williams 2017).

The quasi-peak detector is a peak detector with weighted charge and discharge times which correct for the subjective human response to pulse-type interference. This type of detector is specifically used with respect to measuring the level of interference to voice and broadcast radio signals. Interference at low pulse repetition frequencies (PRFs) is said to be subjectively less annoying on radio reception than that at high PRFs. Pulse-type emissions will be treated more leniently by a quasi-peak measurement than by a peak measurement. But to get an accurate result, the measurement must dwell on each frequency for substantially longer than the QP charge and discharge time constants (Williams 2017).

2.5.2.3 Video Filters

Video filters were the original method used in spectrum analysers to reduce the effects of noise variations in measurements (MIL-STD-461G 2015). In most EMI measurement cases, video filters are specified to be either off, or the video filter is specified to be at least 3 times greater than the specified RBW of the measurement. Video filtering is not allowed to be used in MIL-STD-461G testing. If a controlled video bandwidth is available on the spectrum analyser, it should be disabled or set to its greatest or maximum value (MIL-STD-461G 2015).

2.6 Summary of literature review

The above literature review has addressed the establishment of the background and the brief history of the study of EMI as a critical area of endeavour. Further, the motivation for COTS equipment insertion into the military environment was researched. This research revealed that both political and economical reasons originally drove this motivation, however, the greater efforts of the world's commercial need for technology surpassed the military's ability to keep up with technology, which further drove the this motivation.

Elements of EMI theory and design were researched, covering both conducted and radiated emissions and their behaviour within and between circuits and equipment. As well, elements of the science of EMI measurement were identified and a basis was established, potentially upon which low-cost and practical methods of EMI measurement could be developed.

Research was undertaken into the predominant military and commercial EMI standards to determine the subset of EMI limits and tests that were applicable to the example military environment such as that of a submarine combat system. This provided the basis for determining for a comparison or gap analysis between military requirements and the commercial standards of COTS equipment. Further, this also provided the motivation for the development of a specific pre-compliance scheme to determine the suitability of COTS equipment for insertion into a military, from an EMI standpoint.

Chapter 3

Methodology

3.1 Overview

It has been established that the insertion of COTS ICT equipment within a submarine combat system presents significant challenges for the combat system designer in terms of military EMI compliance. Specifically, the determination of COTS equipment compliance prior to the completion of the system design and final, formal EMI qualification testing. The following methodologies support these two major outcomes:

1. The analysis of COTS EMI standards for conducted and radiated emissions to identify compliance gaps with respect to MIL-STD-461G. These gaps represent risks that the system design will not operate correctly in the intended EMI environment. Such compliance gaps may be identified by comparison of the respective limits, measurement standards or veracity of existing COTS certifications.

2. The development of a means to facilitate the earliest mitigation of this risk is informal (or pre-compliance) testing using readily available, cost-effective laboratory measurement equipment and techniques, semi-formalised as test methods and protocols.

As discussed in Section 2.4.3.1, the applicable MIL-STD-461G requirements are CE101, CE102, RE101 and RE102.

The following methodologies incorporate information, concepts and techniques developed in the previous literature review of Chapter 2, as a review of pre-existing work in relevant areas. Further information is sourced from various standards, equipment manuals and component datasheets. As well, some of the concepts identified in the literature review are further developed in support of specific analyses and design tasks.

3.2 Gap Analysis between COTS EMC standards vs MIL-STD-461G

This methodology underpins the Gap Analysis of Chapter 4.

In the commercial or COTS world, it is most common for vendor information to be limited to a statement of compliance to a commercial EMI standard such as EN55022, AS/NZS CISPR 32 or FCC Part 15, for example. The available evidence is normally, at best, limited to a certificate with such a statement from a certified authority, such as FCC, TUV and ACMA. Very seldom will COTS equipment be supplied with actual test report evidence, showing measurement scans and the actual level of compliance to the relevant standard.

Apart from actual unit testing, the only alternative left to the systems designer wishing to use this COTS equipment in the military environment and to formally document EMI compliance, is to attempt to read across from the relevant commercial standard to the MIL-STD-461G requirements identified above.

This methodology is based on the read-across or comparison of corresponding requirements and criteria between commercial EMI standards and the applicable requirements and criteria of MIL-STD-461G. The intention of these comparisons is to identify compliance gaps between the commercial EMI standards in meeting or exceeding the applicable MIL-STD-461G requirements by means of meeting or exceeding the individual corresponding MIL-STD-461G criteria identified. That is, where the commercial criteria does not meet or exceed the corresponding MIL-STD-461G criteria identified, a compliance gap is identified.

The applicable criteria for comparison are based on those discussed in Section 2.5.2 and are further detailed in the Section 3.2.2, below.

3.2.1 Applicable Commercial EMC Standards

Identifying the commercial EMI standards to be compared to MIL-STD-461G, the following two main criteria are used.

1. EMI standards pertaining to COTS ICT equipment in Australia
2. Other common standards of internationally marketed COTS ICT equipment

European authorities have published and regularly update EMC standards governing many areas of technology. Most other countries follow these standards very closely, if not exactly, as was briefly summarised in Table 2.2. In Australia, ACMA identifies that for Information Technology Equipment (ITE) emissions, AS/NZS CISPR 32 is harmonised with (or equivalent to) CISPR 32 and EN 55032 (Nguyen 2019). For the purposes of this document, the term ITE is equivalent to ICT.

Many existing items of ICT equipment in the COTS market were qualified under EN 55022 or CISPR 22, which was replaced by CISPR 32 in 2017 (EC 2014). CISPR 32, encompasses and replaces several legacy standards including CISPR 11, 14 and 22 (AS/NZS-CISPR-32: 2015). However, for purposes of qualification of ICT equipment, CISPR 22 is essentially equivalent to CISPR 32. Therefore, existing stocks of such equipment, previously qualified to CISPR 22, are in the marketplace and are still considered to be acceptable for use under the current legislation.

Another common qualification for ICT equipment is that of the US Federal Communications Commission, known as FCC Part 15 (Radio Frequency Devices). The limits and measurement methods identified in FCC Part 15, are very similar to CISPR 22 and, in some cases, identical. Most COTS ICT equipment qualified to FCC Part 15, will also carry the CE mark and have CISPR 22 or 32 qualifications as well as other EMI compliance for purposes of international marketing.

Therefore, the commercial EMI standards for COTS ICT equipment to be compared against MIL-STD-461G are rationalised to two main standards for emissions.

1. CISPR 22/32(ITE)
2. FCC Part 15 Subpart B (Unintentional Radiators)

3.2.2 Criteria for Comparison

Criteria compared between commercial EMI standards and MIL-STD-461G was slightly different for conducted emissions and radiated emissions, but are based on the same general ideas.

The comparison of frequency coverage is a simple matter of comparing the frequency ranges of concern between the corresponding emissions standards. The outcome of such a comparison was to clearly identify the gaps between the frequency coverage of those standards and are presented graphically.

The comparison of limits posed a much more complex challenge. Emissions limits are based on several sub-criteria, which are very specific with respect to test set-up and ancillary equipment, as well as detector types and resolution bandwidths, which were explained in Section 2.5.2. The main criteria on which the various commercial and military emissions standards are based, include the following (Paul 2006, DoD 2001, Agilent 1998).

- In the case of radiated emissions:
  - The specific measurement antenna type, which affects emission signal measured amplitude and, in some cases, the associated measurement units;
  - The specific distance between the EUT and the measurement antenna, which affects the amplitude of received emission signal;
- In the case of conducted emissions:
  - The specific test set-up (circuit) layout and ancillary equipment to be used, which can affect the emission signal measured amplitude;
  - The specific sensor or test point, which affects emission signal measured amplitude and, in some cases, the associated measurement units;
- The specific detector type of the measuring instrument, which can affect the emission signal measured amplitude; and
- The specific Resolution Bandwidth settings and dwell times of the measuring instrument, which can affect the emission signal measured amplitude.

These criteria have been summarised for MIL-STD-461G in Table 2.7 and were used as the criteria for comparison of the commercial standards identified in Section 3.2.1. These criteria are not an exhaustive list. Other specific details could include grounding, facilities, and other minutia, very specific to individual circumstances and types of EUTs. However, for the purposes of this study, their importance was assumed to be negligible.

3.2.2.1 Distance between EUT and Measurement Antenna

One particularly critical criterion (or parameter) that directly affects the setting of an EMI limit for radiated emissions is the distance from EUT at which the measurement antenna is placed. As discussed at length in Sections 2.3.2.4 and 2.3.2.5, the greater the distance from the source of radiation, the lower the field intensity. Therefore, notwithstanding the gain of the measurement antenna, the further the specified distance between the EUT and the antenna, the lower the expected signal that can be sensed by the antenna.

As seen in Section 2.4.5, MIL-STD-461G specifies a test distance of one metre. CISPR and FCC standards specify test distances of three to ten metres and have limits stated for those distances. Therefore, there was a requirement to scale these limits to a measurement distance of one metre, in order to compare them to the requirements of MIL-STD-461G. A simple mathematical formula was developed from a Path Loss expression derived from the Friis Transmission Formula of Section 2.3.2.5 and can be applied to achieve this.

Expanding the term for Path Loss (in dB) of Equation 2.16, with the power ratio of Equation 2.15.

$$PL\,(dB) = P_r\,(dB) - P_t\,(dB) = G_t\,(dB) + G_r\,(dB) + 20\log\left(\frac{\lambda}{4\pi r}\right) \tag{3.1}$$

Letting P_{r1} be the power received at a distance r_1 and P_{r2} be the power received at another distance r_2. The difference in Path Loss or ΔPL in dB can be found for the movement of the receiving antenna from r_1 to r_2.

$$\begin{aligned} \Delta PL\,(dB) &= P_{r1}\,(dB) - P_t\,(dB) - (P_{r2}\,(dB) - P_t\,(dB)) \\ &= P_{r1}\,(dB) - P_{r2}\,(dB) \end{aligned} \tag{3.2}$$

Expanding this to include all the terms in Equation 3.2,

$$\begin{aligned} P_{r1}\,(dB) - P_{r2}\,(dB) = G_t\,(dB) + G_r\,(dB) + 20\log\left(\frac{\lambda}{4\pi r_1}\right) \\ - \left(G_t\,(dB) + G_r\,(dB) + 20\log\left(\frac{\lambda}{4\pi r_2}\right)\right) \end{aligned} \tag{3.3}$$

Which simplifies to a form that clearly shows that the power received at r_2 can be calculated (or scaled) from the power received at r_1.

$$P_{r2} = P_{r1} + 20\log\left(\frac{r_1}{r_2}\right) \tag{3.4}$$

Section C.2.2.4 of AS/NZS CISPR 32 also provides guidance that limits may be scaled for non-standard distances of the measurement antenna from the EUT, using this formula.

However, as stated in Section 2.3.2.5, the transmission formula is only accurate for the condition where the relation in Equation 2.17 is true. As r becomes smaller, far-field conditions start to transition to near-field conditions, and specific details of the EUT's and measurement antenna's physical geometry start to play a dominating role. In practice, far-field measurement antennas cannot just be brought arbitrarily closer to the EUT with the expectation that the formula described by Equation 3.4 will produce accurately adjusted limits. The smaller the measurement distance, the more the physical dimensions and shapes of both the EUT and the measurement antenna becomes critical. Figure 3.1 show the disparity between various standards with respect to frequency span and potential near-field vs far-field coupling.

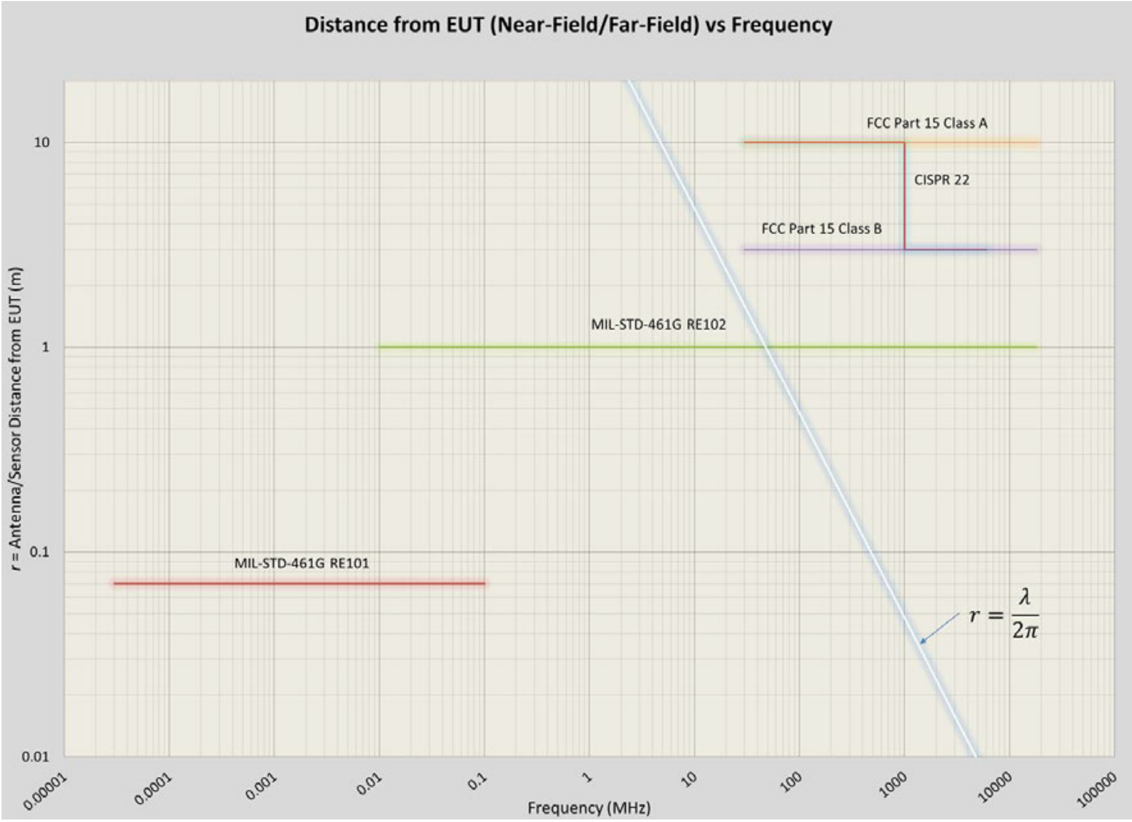


Figure 3.1: General comparison between commercial standards and MIL-STD-461G requirements with respect to potential near-field vs far-field coupling.

As this Gap Analysis is based purely on the theoretical movement of the measurement distance by means of mathematical adjustment, it is expected that the practicalities of antenna shapes and directivity may be disregarded.

3.2.2.2 Measurement Instrument Settings

Other critical criteria that directly affect the value of an EMI limit are the prescribed settings of the measurement instrument(s). For example, the detector type and the resolution bandwidth. As clearly summarised in Table 2.7, MIL-STD-461G requires a peak detector mode, specific RBW settings and is also specific about minimum measurement dwell times. It is to these parameters that the MIL-STD-461G limits have been set.

Therefore, any correct comparison with other emissions standards required either the same instrument settings to be met, or settings that would give a worse-case result such that their specified limits are not artificially understood to be equivalent to those of

MIL-STD-461G.

For example, in the case of RBW, if a commercial standard identifies that its limit at a certain frequency is set with guidance that its test measurement receiver is to be set at 120 kHz and the MIL-STD-461G limit for the same frequency requires an RBW setting of 100 kHz, the commercial limit would be comparable as its corresponding test readings would be a worse-case than that of MIL-STD-461G. If the MIL-STD-461G limit for the same frequency requires an RBW setting of 1 MHz, the same commercial limit must be seen as non-compliant, as its RBW of 120 kHz will artificially reduce the amplitude of its test readings at that frequency, for the reasons discussed in Section 2.5.2.1. However, if the commercial limit for that frequency is lower than the MIL-STD-461G limit by a considerable margin, its test readings at that frequency, would likely not exceed the corresponding MIL-STD-461G limit.

Similarly, the compatibility of specified detector types is also a critical parameter that directly affects the value of an EMI limit. As discussed in Section 2.5.2.2, the specific detector type will affect the test measurement reading. MIL-STD-461G requires only peak detectors to be used. However, many commercial standards specify average or quasi-peak detectors, which by their nature will likely give lower test measurement readings.

For example, if a commercial standard identifies that its limit at a certain frequency is set with guidance that its test measurement receiver is to use a an averaging or a quasi-peak detector, the commercial limit will not be directly comparable to that of MIL-STD-461G, as its corresponding test readings will tend to be lower than that of a MIL-STD-461G peak detector. However, if the commercial limit for that frequency is lower than the MIL-STD-461G limit by a considerable margin, it may be considered a worse-case than the corresponding MIL-STD-461G limit.

This margin is almost an arbitrary figure due to the non-linear nature of the way that both quasi-peak and averaging detectors function, which was discussed in more detail in Section 2.5.2.2. While it is a function of weighting with respect to repetition rates and instrumentation time constants, the following are reasonable rules of thumb that can be applied to compare peak, quasi-peak and average limits (Schwartzbeck n.d., Tektronix 2016).

- A quasi-peak value of -10 dB or less than a comparison peak value is likely to be similar to or less than the peak value of the same signal, and

- An average value of -20 dB or less than a comparison peak value is likely to be similar to or less than the peak value of the same signal.

These rules of thumb are also evident in some commercial standards where an average limit is quoted with a corresponding quasi-peak limit or an average limit is quoted with peak limit. For example, the conducted and radiated emissions limits stated for both CISPR 22/32(ITE) and those for FCC Part 15 Subpart B as detailed later in Tables 4.3, 4.6 and 4.10, respectively. It was seen to be a common that when both an average value and a quasi-peak value is stated for the same limit, the quasi-peak value is 10 dB higher than the average value; as well, when both an average value and a peak value is stated for the same limit, the peak value is 20 dB higher than the average value. Therefore, when comparing commercial standards stated in average or quasi-peak values to MIL-STD-461G peak values, it is appropriate to extrapolate a peak value from the commercial limits for comparison to the military limits, using the above rules of thumb.

Dwell time is another criterion which affects the setting of an emissions limit. However, since the commercial standards state the use of averaging and quasi-peak detectors, their minimum dwell times are well in excess of MIL-STD-461G requirements for minimum dwell times and is therefore, not of concern with respect to this study.

3.2.3 Presentation of Comparisons and Compliance Gaps

The presentation of the Gap Analysis was based on the following steps:

1. Collation and tabulation of corresponding emissions requirements
2. Graphical comparison of frequency coverage
3. Normalisation and scaling of limits and units where necessary and appropriate
4. Graphical comparison of normalised limits
5. Tabulation and short narratives compiled in a summary compliance matrix (with traffic lights indication of compliance levels)

This was then followed with a simple narrative conclusion addressing each MIL-STD-461G requirement and the resultant compliance gap of each corresponding commercial standard.

3.3 MIL-STD-461G Pre-Compliance Test Design

This methodology underpins the pre-compliance test design of Chapter 5.

While formally accredited test laboratories are required to make highly accurate MIL-STD-461G EMI measurements with traceably calibrated prescribed equipment, sensors and facilities as shown in Figure 3.2, pre-compliance testing does not have this burden.

Figure 3.2: Typical Semi-Anechoic Chamber suitable for MIL-STD-461G compliance testing (frankonia-solutions.com)

As discussed in Section 2.5, the intention of pre-compliance testing of COTS ICT equipment is to achieve a pre-design understanding (or characterisation) of the EMI performance and level of compliance of that equipment to MIL-STD-461G requirements. This data can then be used by the system designers to determine the level of risk on downstream non-compliance of the system, using that COTS ICT equipment. It also provides key details, such as frequencies and levels, for the system designers to be able to provide protections and EMI hardening measures to either attenuate or eliminate any overly risky areas of non-compliance, using some of the EMI Design techniques discussed in Section 2.3.5.

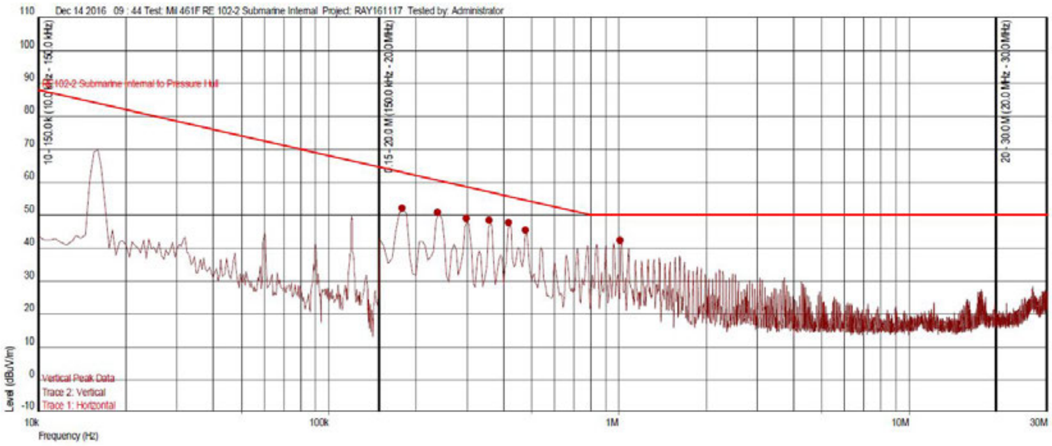


Figure 3.3: Typical example of a partial (10 kHz to 30 MHz) MIL-STD-461G RE102 formally calibrated scan (austest.com.au)

In developing a simplified and practical set of pre-compliance test protocols in accordance with MIL-STD-461G, the following steps were required.

- Identification of the subset of test requirements that must be met.
- Analysis of the MIL-STD-461G test configurations for those specific requirements in order to determine the hardware and facility requirements to be used as an objective to be approximated, simplified or even discarded with appropriate justification.
- Identification of limitations due to practicality. One major limitation was the maximum frequency that can be tested, which was limited to 1 GHz due to available resources, cost and time.
- Selection and procurement or design and construction of test hardware and supporting materials, equipment and facilities.
- Selection and procurement of measurement equipment that either mets or exceeded the requirements of MIL-STD-461G for a measurement receiver and data recording device.
- Calibration and verification of the operation of the hardware and test configurations within the chosen facility arrangement. In many cases, MIL-STD-461G provides some guidance required to develop calibration and verification procedures.

- Development of pre-compliance test configurations and associated test steps to follow or approximate the corresponding MIL-STD-461G test configurations and steps as closely as possible.
- Development of an appropriate means of presenting measurement results for comparison against MIL-STD-461G limits corresponding to the identified requirements.

3.3.1 Applicable MIL-STD-461G Requirements

As stated in the Overview, the applicable subset of MIL-STD-461G test requirements that must be met are as per Section 2.4.3.1.

In addition to the specific hardware and supporting equipment needed to undertake individual pre-compliance tests in accordance with these requirements, there are some general hardware and facilities requirements common to all tests.

3.3.2 Basic Facilities and Common Hardware

Based on the MIL-STD-461G recommended general test setup as illustrated in Figure 3.4, the following is a list of facilities and support hardware requirements that was common to all tests.

- The most critical requirement to meet was that the configured facility must be electrically safe.
- The selection of a reasonable room based on the fact that a screened arrangement is beyond the scope of an open laboratory environment. There was not much choice in the selection of such a facility, regardless of ambient RF noise or size limitations. The minimum requirement to be met was that the ambient noise did not disguise the bulk of the measurable spectrum and that antennas could be placed at 1 m from the EUT for radiated measurements.
- While there is guidance in MIL-STD-461G which demands at least 2.5 m of ground plane around the test configuration, this was limited by the cost of ground plane materials and available space. The grounding scheme and ground plane arrangement was based on electrical safety, on maximum coverage and on the reasonable selection

of material based on good conductivity, best RF performance (such as skin effect), availability and cost.

- Provision of an isolated 115 VAC, 60 Hz mains supply with circuit protection. Due to limitations of resources such as a static power converter, normal 50 Hz power may need to be used to energise the EUT.

- The LISN design was based on the MIL-STD-461G reference design as discussed in Section 2.4.3.3 and good, high-frequency design techniques.

- In the interests of being able to compare readings over some part of the spectrum to verify their operation, the selection of at least two spectrum analysers with tracking generators, capable of measurements covering the entire frequency range of interest, including conducted and radiated requirements (30 Hz to 1 GHz). Other critical selection criteria:

  - Provision of suitably adjustable RBW and the availability of Gaussian-shaped IF-filtering with 6 dB form-factor as described in Section 2.5.2. A 3 dB form-factor is acceptable in accordance with MIL-STD-461G.

  - Deselection of VBW or the ability to select a VBW value at least ten times higher that than the RBW.

  - The availability of a peak detector compliant with MIL-STD-461G.

  - The ability to record data to a readily accessible medium.

- Provision of various supply and measurement cables of known performance as required.

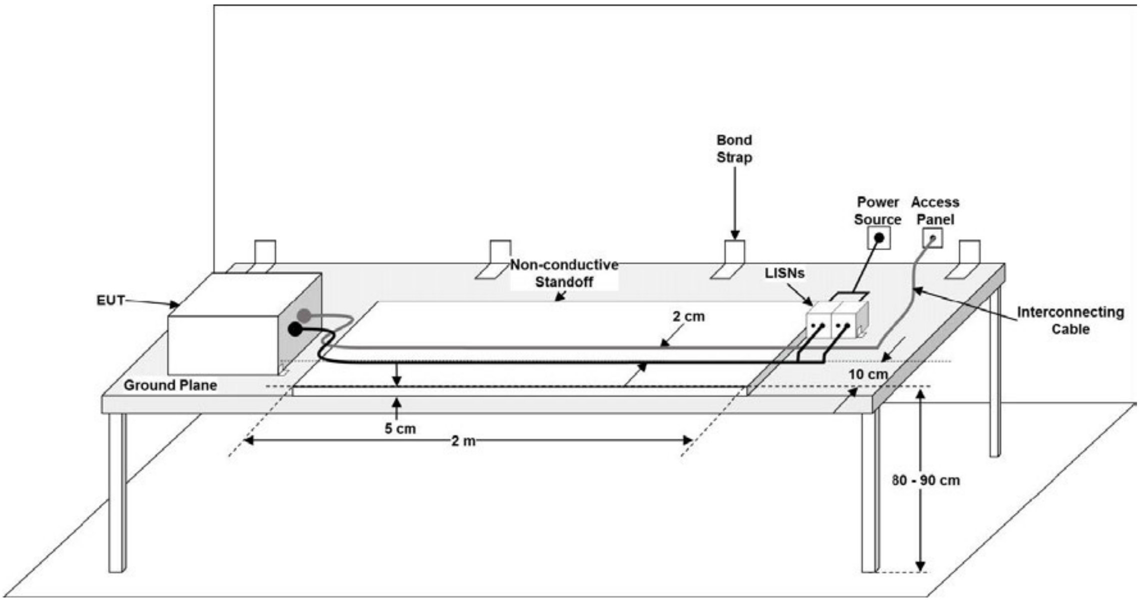


Figure 3.4: MIL-STD-461G general test setup (MIL-STD-461G 2015)

In formally controlled tests, a shielded room or Semi Anechoic Chamber (SAC), as illustrated in Figure 3.2, with heavily filtered power is used to greatly attenuate or even eliminate virtually all background RF noise and reflections, which increases the dynamic range of measurements taken within that environment. However, in pre-compliance testing, it is usually not of great value to virtually eliminate all background noise. It is more practical and a lot cheaper to just make sure that there is a reasonable gap, where possible, between the average background noise level and the limit levels that the EUT is expected to meet.

In this way, most major emissions from the EUT can usually be identified readily. In extreme cases, where background noise is overwhelming, it may be necessary to relocate to a quieter (in terms of RF) area, if possible. Alternatively, if possible, turn off or otherwise disable the sources of noise.

Various specific sensors, other support components and equipment was required to be procured or developed, approximately based on those specified in the MIL-STD-461G standard. These simplified items required calibration and testing to prove their reasonable operation. Rationale and detailed design calculations are shown in support of selection of materials, components, equipment settings and configurations.

3.3.3 Arithmetic conversions between logarithmic units

For a test system with standard input and output impedances, such as 50 Ω, simple arithmetic conversion factors can be applied to quickly convert readings in one unit to another, more appropriate unit, if necessary.

For such a system, the basic reference power level is that of 1 mW into 50 Ω (or any other standard system impedance for that matter) and is measured in dBm. For example:

$$P \ \ (dBm) = 10 \ \times LOG \left(\frac{P}{1 \times 10^{-3}} \right) \tag{3.5}$$

Therefore, for $P = 1$ mW, the value for P in dBm will be:

$$10 \ \times LOG \left(\frac{P}{1 \times 10^{-3}} \right) = 0 \ dBm \tag{3.6}$$

For conversion to dBμV in a 50 Ω impedance:

$$0 \ dBm = 10 \ \times LOG \left(\frac{V^2/50}{1 \times 10^{-3}} \right) \tag{3.7}$$

Rearranging and finding the value for $V = 0.224$ mVrms and then converting into dBμV:

$$20 \ \times LOG \left(\frac{0.224}{1 \times 10^{-6}} \right) = 107 \ dB\mu V \tag{3.8}$$

Also, for conversion to dBμA in a 50 Ω impedance:

$$0 \ dBm = 10 \ \times LOG \left(\frac{I^2 \times 50}{1 \times 10^{-3}} \right) \tag{3.9}$$

Rearranging and finding the value for $I = 4.472$ mArms and then converting into dBμA:

$$20 \ \times LOG \left(\frac{4.472 \times 10^{-3}}{1 \times 10^{-6}} \right) = 73 \ dB\mu A \tag{3.10}$$

Therefore, it can be seen that for a 50 Ω impedance:

$$0\ dBm \ = \ 107\ dB\mu V \ = \ 73\ dB\mu A \tag{3.11}$$

From Equation 3.11, conversion factors between between units of power, voltage and current can be derived for a 50 Ω impedance system. Because they are in logarithmic values, these factors are simply added or subtracted to apply the conversion. Table 3.1 shows some of the most useful conversions.

dBm	**dBμV**	**dBμA**
dBμV - 107	dBm + 107	dBm + 73
dBμA - 73	dBμA + 34	dBμV - 34

Table 3.1: Some of the most useful conversion factors between logarithmic units

3.3.4 Specific Hardware Requirements for the CE101 Test Configuration

CE101 is a Conducted Emissions measurement for audio frequency currents on power leads as discussed in Section 2.4.4.1. In summary, the following items were built or procured in order to develop a test configuration to allow CE101 testing to be executed.

- Selection, calibration and verification of a suitable current probe (or current clamp) arrangement that will operate over at least the frequency span of CE101 (30 Hz to 10 kHz). However, as discussed in Section 2.4.4.1, the standard directs that the lowest frequency of concern for an AC fed EUT is twice the nominal AC supply frequency. Figure 3.5 shows typical, professionally manufactured current probes.
- Measurement equipment capable of accurately measuring the output of the current transformer over the appropriate frequency span.
- Ability to provide the measurement in the appropriate units of dBμA.

The key parameters for the selection of the current probe are that it is capable of operating over the frequency range of interest and that it has sensitivity sufficient to provide an output for the purposes of verifying that the signal currents being measured are below the limits as described in Figure 2.20 in units of dBμA. Also, since the probe measures the entire AC load current supplied by the power lines as illustrated in Figure 3.6, it must be able to operate over the range of possible load currents likely to be present in powering the EUT and not saturate.

For the purposes of this project, such a current sensor should be able to operate correctly with a supply current of up to 10 amperes, at the fundamental supply frequency.

Figure 3.5: Typical current probe clamps (Wyatt 2012)

Figure 3.5, shows typical current probes specifically designed for EMI measurement. These items are usually priced between about one and two thousand dollars and are usually provided with detailed and certified calibration data. Due to cost, it will be necessary to find an alternative sensor.

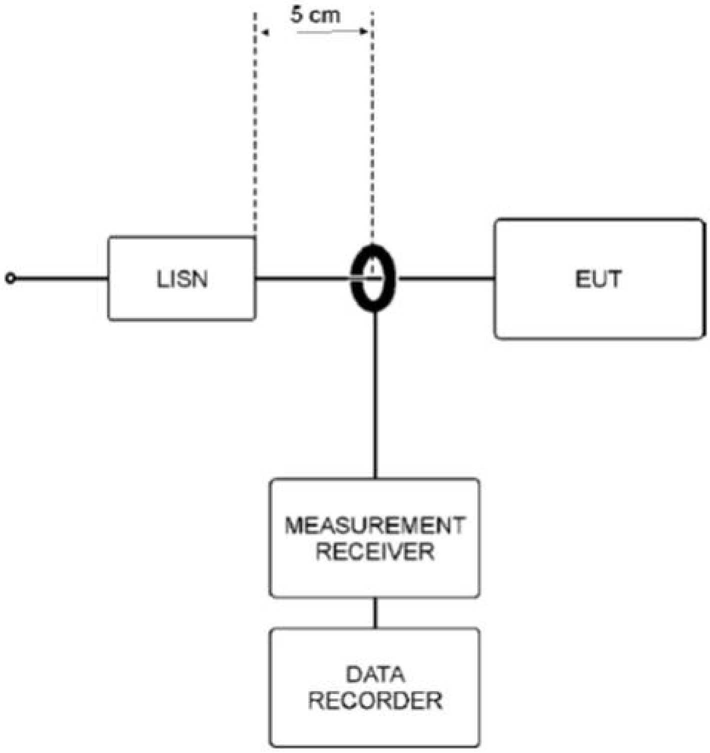


Figure 3.6: General test setup for CE101 (MIL-STD-461G 2015)

In order to test and calibrate such an alternative current clamp, it was necessary to investigate its intended operation in detail. Figure 3.7, shows the basic operation of such a clamp as used for EMI Measurement. Ultimately, the clamp is meant to drive the 50 Ω input of a spectrum analyser, which will be able to measure the voltage V in rms volts . The spectrum analyser can also provide this measurement in the logarithmic form in units of dBμV. The units required for comparison to the CE101 limits of Figure 2.20 are in dBμA.

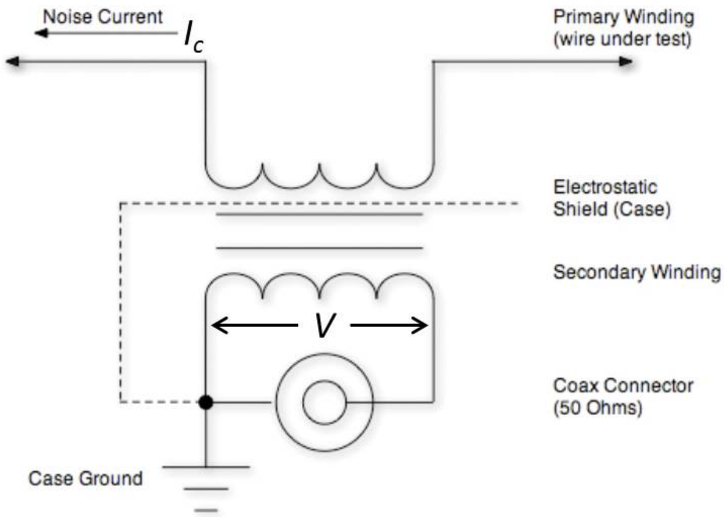


Figure 3.7: Schematic diagram view of current probe operation (Wyatt 2012)

As seen in Figure 3.7, the current I_C, which is ultimately the measurand of interest, is related to voltage V via the operation of the current clamp. The term "transfer impedance", Z_T, is used to define this relationship (Wyatt 2012), and is stated in units of ohms.

$$Z_T = \frac{V}{I_C} \tag{3.12}$$

This can be re-written in terms of dBs, using the units which are required:

$$Z_T \ \ (dB\Omega) = V \ \ (dB\mu V) - I_C \ \ (dB\mu A) \tag{3.13}$$

Where Z_T or the transfer impedance is the calibration factor and can be applied by simply adding Z_T in dBΩ to the value of V in dBμV, read from by the spectrum analyser to give I_C in dBμA, as required for CE101 measurements.

$$I_C \ \ (dB\mu A) = V \ \ (dB\mu V) + (-Z_T) \ \ (dB\Omega) \tag{3.14}$$

Calibration data for the clamp is collected by injecting test signals in the primary of the clamp by passing a known current through the primary. This is accomplished by connecting a signal generator as illustrated in Figure 3.8.

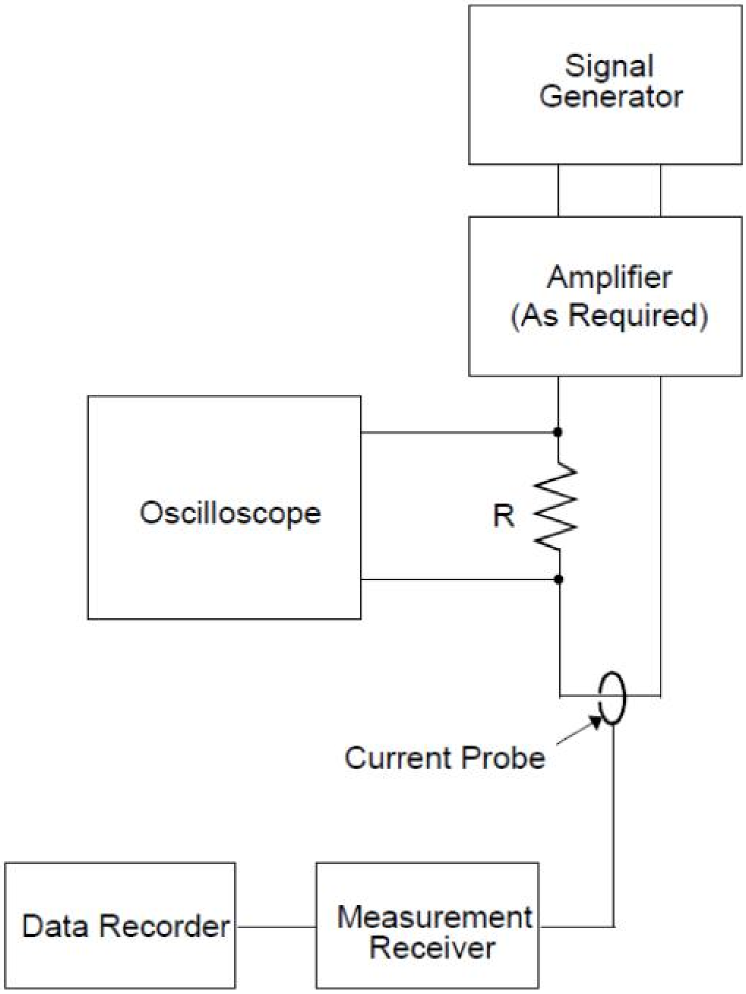


Figure 3.8: Clamp calibration setup (MIL-STD-461G 2015).

The calibration data for the clamp must be measured at least over the CE101 frequency span of interest and such measurements should be taken as a minimum at frequency increments of at least one tenth of a decade, as shown in Table 3.2.

Frequency Range	**Frequency Increment**
10 Hz - 100 Hz	10 Hz
100 Hz - 1000 Hz	100 Hz
1000 Hz - 10000 Hz	1000 Hz

Table 3.2: Minimum calibration intervals for CE101

3.3.5 Specific Hardware Requirements for the CE102 Test Configuration

CE102 is a Conducted Emissions measurement for noise voltages on power leads as discussed in Section 2.4.4.2. In summary, the following items were built or procured in order to develop a test set-up or configuration to allow CE102 testing to be executed.

- Calibration and verification of the LISN's measurement output over at least the frequency span of CE102 (10 kHz to 10 MHz).
- Measurement equipment capable of accurately measuring the output of the LISNs over the appropriate frequency span.
- Ability to provide the measurement in the appropriate units of dBμV.

CE102 requires two LISNs as per Figure 3.4, and of the type discussed in Section 2.4.3.3. These may be purchased, however, they can cost in excess of one thousand dollars each. Therefore, for the purposes of this project, the two LISNs were both hand-built.

The LISN design provides for a direct voltage measurement port with an output impedance of 50 Ω, which may be connected directly into a 50 Ω measuring device such as spectrum analyser. However, it is recommended that a transient limiter and a 20 dB attenuator be used in series with the spectrum analyser to protect it from mains surges and spikes, as per MIL-STD-461G.

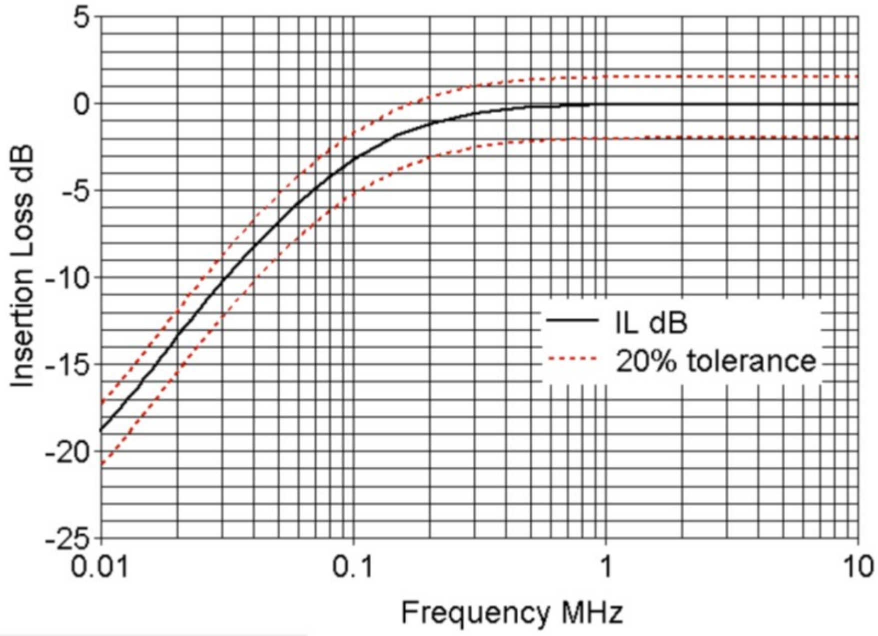


Figure 3.9: LISN insertion loss curve as per SAE AIR6236

A properly constructed LISN should have an insertion loss as per Figure 3.9. This is verified by measuring it in accordance with SAE AIR6236, *In-house verification of EMI test equipment*, Section 3.2, as illustrated in Figure 3.10.

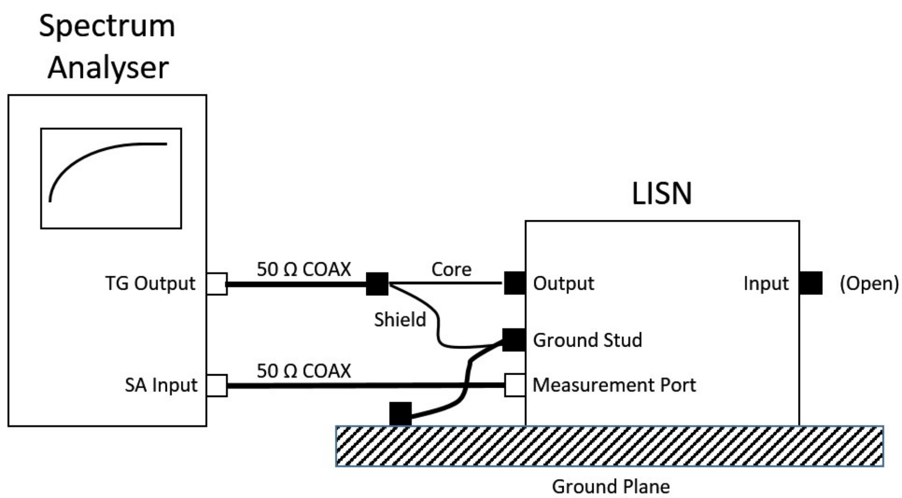


Figure 3.10: LISN insertion loss measurement adapted from SAE AIR6236

The insertion loss, IL, of the LISN should be measured in dB to be within the 20% band as shown in Figure 3.9. The correction factor should be determined as per the expression:

$$CF = -IL \tag{3.15}$$

These correction factors should be compiled over the frequency span of interest of CE102 at frequency increments of at least one tenth of a decade, as shown in Table 3.3.

Frequency Range	**Frequency Increment**
10 kHz - 100 kHz	10 Hz
100 kHz - 1 MHz	100 kHz
1 MHz - 10 MHz	1 MHz

Table 3.3: LISN minimum calibration intervals for CE102

A verification procedure for the LISNs proper operation is found in MIL-STD-461G, Section 5.5.3.4a *Measurement system integrity check*, which is based on supplying a monitored test signal at the LISN output and verification of the correct value measured at the LISN's measurement port, as illustrated in Figure 3.11.

It should be reinforced here for safety reasons that, while under verification, all LISNs must be physically disconnected from any AC supply. As well, the ground plane and all other earth connections should be verified as having no more than 100 mΩ impedance to the facility's safety earth system.

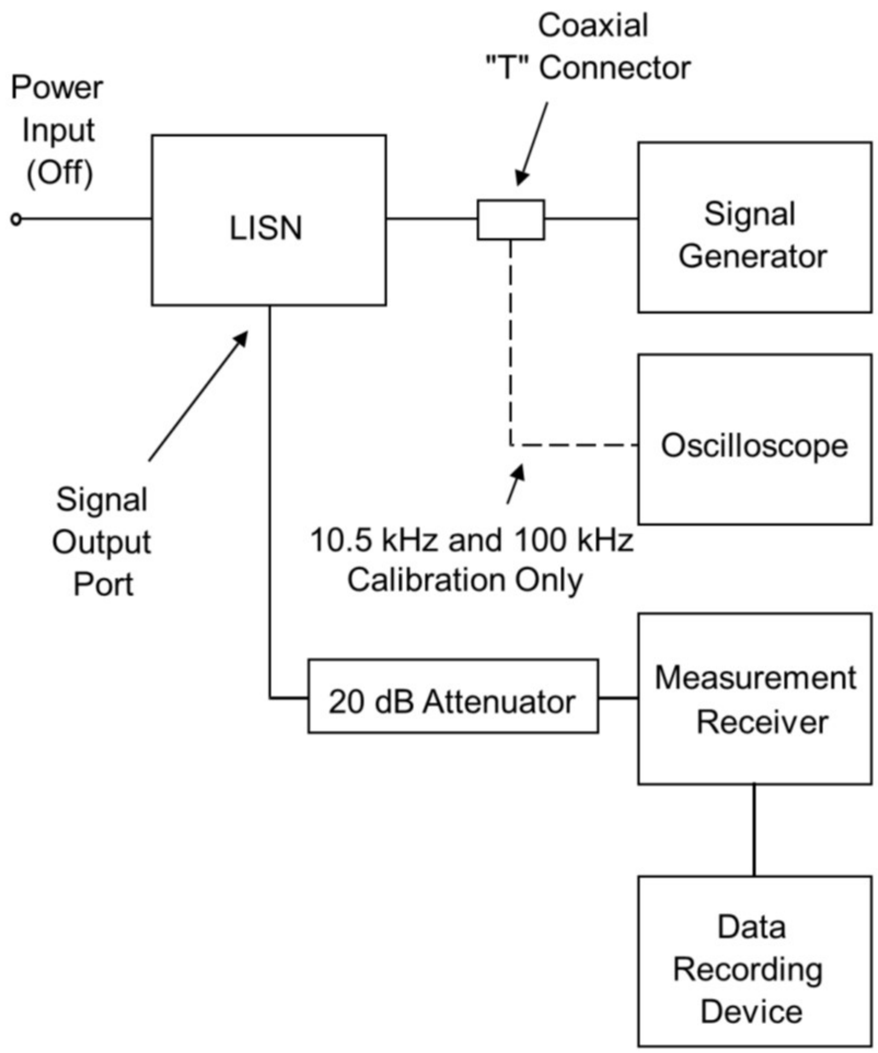


Figure 3.11: CE102 LISN verification setup (MIL-STD-461G 2015)

3.3.6 Specific Hardware Requirements for the RE101 Test Configuration

RE101 is a radiated emissions, magnetic field measurement made at a distance of 7 cm from the EUT as discussed in Section 2.4.5.1. In summary, the following items were built or procured in order to develop a test set-up or configuration to allow RE101 testing to be executed.

- Procure or make RE101 magnetic sensor loop antenna.

- Calibration and verification of the loop sensor over at least the frequency span of RE101 (30 Hz to 100 kHz).
- Measurement equipment capable of accurately measuring the output of the loop sensor over the appropriate frequency span.
- Ability to provide the measurement in the appropriate units of dBpT.

Figure 3.12: Typical RE101 loop antenna (solar-emc.com)

The RE101 magnetic sensor loop antenna is described in some detail in MIL-STD-461G and is the same for previous versions of the standard under the superseded requirement RE01. This type of loop antenna is readily available, pre-calibrated, from several EMI measurement supply vendors. An example is shown in Figure 3.12. However, was quoted in excess of $2000 dollars. Therefore, it was necessary to construct one and calibrate it using the published procedures as per SAE ARP958D.

The key parameters for the design of the RE101 loop antenna are as follows.

Loop Diameter:	13.3 cm
Wire Type:	7 Strand, 41 AWG Litz
Number of turns:	36 turns
Loop Shielding:	Electrostatic
Series resistance:	Between 5 Ω and 10 Ω

As described in SAE ARP958D, the calibration of the RE101 loop antenna is based on the use of another, standard loop antenna that is used for MIL-STD-461A RS01 susceptibility testing, which is not discussed in this document. However, this well established design is based on a well proven and simple technique whereby a controlled current is passed through the RS01 loop, providing a guaranteed magnetic field strength at a precise distance of twelve centimetres.

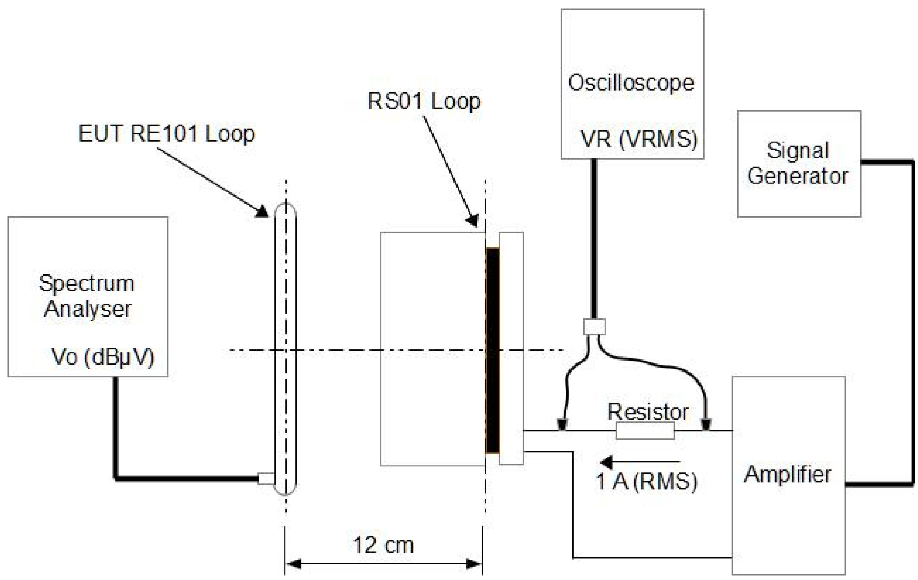


Figure 3.13: RE101 Loop Antenna calibration setup as adapted from SAE ARP958D

The RS01 loop is a very simple construction based on ten turns of 16 AWG enamelled copper wire around a circular former of 12 cm diameter. An original construction diagram for the RS01 loop, extracted from MIL-STD-461A, can be seen in Appendix B.

The calibration setup for the RE101 loop antenna, as illustrated in Figure 3.13, utilises the RS01 loop to generate a known magnetic a field strength based on a controlled 1 A current through the generating loop. The oscilloscope is used to verify the voltage across the resistor, which, in turn controls the exact current through the coil of the RS01 loop.

In accordance with the guidance of SAE ARP958D, the following expression is used to calculate the field strength at a distance of 12 cm from the edge of the RS01 loop:

$$B = \frac{\mu_o I N R^2}{2\sqrt{(R^2 + Z^2)^3}} \tag{3.16}$$

Where:

B is magnetic field strength in Tesla,

μ_o is the permeability of free space in H/m,

I is the current through the RS01 loop A rms,

N is the number of turns of wire in the RS01 loop,

R is the radius of the RS01 loop, and

Z is the distance between RE101 loop and the RS01 loop in metres.

With a current of 1 ampere (rms) through the RS01 loop as shown in Figure 3.13, the magnetic field strength, B at the RE101 loop, 12 cm away is 9.366 μT. B in dB with reference to 1 pT is 139.4 dBpT.

The method of RE101 loop calibration is to measure the output voltage, V_o, of the 50 Ω-loaded loop in dBμV for various frequencies swept by the signal generator. The oscilloscope is used to verify that the voltage drop across the resistor is adjusted to guarantee a 1 A(rms) current through the generating loop.

For every frequency signal measured, the antenna factor, AF in dB, is determined by subtracting the V_o from B.

$$AF = B - V_o \tag{3.17}$$

The calibration data for the RE101 loop must be measured at least over the RE101 frequency span of interest and such measurements should be taken as a minimum at frequency increments of at least one tenth of a decade, as shown in Table 3.4.

Frequency Range	Frequency Increment
30 Hz - 100 Hz	10 Hz
100 Hz - 1 kHz	100 Hz
1 kHz - 10 kHz	1 kHz
10 kHz - 100 kHz	10 kHz

Table 3.4: Minimum calibration intervals for RE101

3.3.7 Specific Hardware Requirements for the RE102 Test Configuration

RE102 is a radiated emissions, electric field measurement made at a distance of 1 m from the EUT as discussed in Section 2.4.5.1. In summary, the following items were built or procured in order to develop a test set-up or configuration to allow RE102 testing to be executed.

- Procure or make RE102 electric field strength measurement antennas as per Section 2.4.5.2.
- Calibration and verification of the electric field antennas over their individual spans to cover the RE102 frequency span as identified for this project (10 kHz to 1 GHz).
- Verify measurement equipment capable of accurately measuring the output of the electric field antenna's frequency spans in or der to cover the entire appropriate frequency span.
- Ability to provide the measurement in the appropriate units of dBμV/m.

Due to the very wide band of coverage, RE102 testing typically requires several antennas to be employed across the measurement band. As discussed in Section 2.4.5.2. For the purposes of this project, the following antennas are required.

- A 104 cm rod antenna for use between 10 kHz and 30 MHz. Noting that this antenna's frequency range is entirely within the theoretical near-field, its geometrical shape will almost certainly be critical to its performance in this context. Therefore, in order to try to maintain consistency with formal RE102 testing, this geometrical shape presents a lower risk. As it is a very simple arrangement of a 104cm long rod, mounted vertically over a 60 cm square counterpoise or ground plane, it can easily be constructed.

- A biconical antenna for use between 30 MHz and 200 MHz. As with the 104cm rod antenna, this biconical design is a well established and a specified geometrical design meant to operate in the frequency range which covers the theoretical transition zone between near and far fields. As such, its geometrical shape is likely critical to its measurement performance for the same reasons. While this antenna is more challenging to construct, it is very well documented in the form of detailed construction drawings as part of MIL-STD-461A. Therefore, it is intended that this antenna will also be constructed.
- A log-periodic antenna for use between 200 MHz and 1 GHz - this is meant as a replacement for the large dual-ridged horn specified by MIL-STD-461G as illustrated in Figure 2.29. This alternative antenna is required as the dual-ridged horn typically costs well in excess of $3000 and is not readily hand-made. As the frequency range of 200 MHz to 1 GHz is well inside the far field, the geometrical shape of this antenna is much less likely to matter to its measurement performance. The log-periodic design is very similar to commoner-garden television (VHF/UHF) antennas, which typically cover this range of frequencies and should be adaptable for this purpose.

As directed in MIL-STD-461G, antennas are to be calibrated in accordance with standards SAE ARP958 and ANSI C63.5. These standards provide several methods for such calibration. The higher frequency types of antenna require a different method of calibration. One practical method that lends itself to this application is the two identical antenna method (SAE 2003, MIL-STD-461G 2015). This requires that two of every antenna to be made or procured. Hence, the importance of low cost and a focus on simplicity.

3.3.7.1 The 104cm Rod Antenna calibration method

Figure 3.14: Typical 104 cm rod antenna (theemcshop.com)

The 104 cm Rod (or monopole) Antenna, as illustrated in Figure 3.14, is the lowest frequency electric field antenna. It has a prescribed method of calibration referenced by MIL-STD-461G via both SAE ARP958 and ANSI C63.5, using what is termed as the Equivalent Capacitance Substitution Method (ECSM).

In this method, illustrated in Figure 3.15, the rod portion of the antenna is replaced (or substituted) by an equivalent capacitance assembly. This equivalent capacitance is fed by a signal generator, then the output from the impedance matching network of the antenna is measured. to reduce uncertainty, the input voltage to the dummy antenna is also measured. The antenna gain, G, measured in units of dB(1/m) is given by Equation 3.18.

$$G = V_D - V_L + 6.02 \tag{3.18}$$

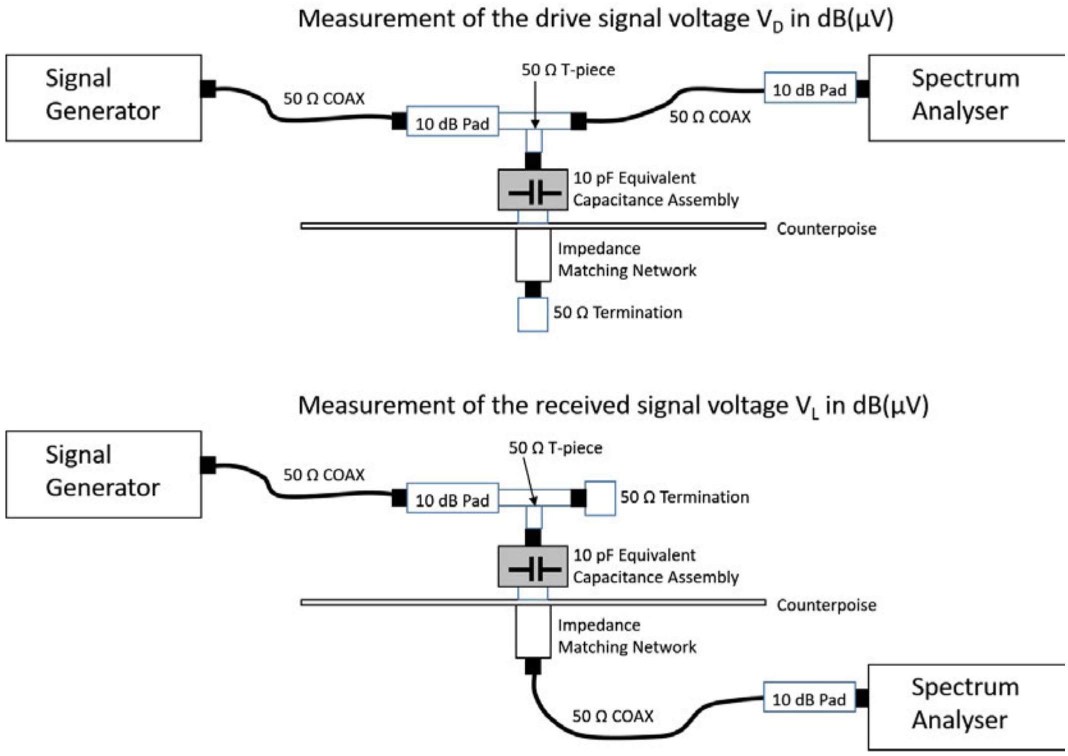


Figure 3.15: 104cm Rod Antenna calibration "Equivalent Capacitance Substitution Method" setup adapted from ANSI C63.5

Measurements of V_D and V_L should be taken, as a minimum, at frequency increments of at least one tenth of a decade, as shown in Table 3.5.

Frequency Range	Frequency Increment
10 kHz - 100 kHz	10 kHz
100 kHz - 1 MHz	100 kHz
1 MHz - 10 MHz	1 MHz
10 MHz - 30 MHz	10MHz

Table 3.5: Minimum calibration intervals for the 104 cm Rod Antenna

Calculations to develop the Antenna Factor, AF, for the rod antenna are the same as that for the higher frequency antennas, defined in the next section. Specifically, the formula of Equation 3.35. This Antenna Factor is then applied to the formula of Equation 3.36 to determine the electric field strength immediately adjacent to the rod antenna in dBμV/m.

3.3.7.2 Higher frequency electric field antenna calibration method

For higher frequency electric field antennas, such as the Biconical and the Log-Periodic Distributed Array (LPDA), a technique called the *two identical antenna method* may be used for calibration. Examples of these antennas are shown in Figures 3.16 and 3.17, respectively.

Figure 3.16: Typical shape of a MIL-STD-461 style, biconical antenna (com-power.com)

In this technique, two identical antennas are arranged as in Figure 3.18. One is transmitting and the other is receiving. This technique takes advantage of the laws of antenna pattern reciprocity. With the spectrum analyser and tracking generator configured as a scalar network analyser set up to measure the insertion loss of the antenna system.

Figure 3.17: Typical LPDA EMI antenna (com-power.com)

While the requirement of two identical antennas of each type used adds to effort and cost, a useful outcome was the availability of a calibrated spare, should one antenna be damaged and become unserviceable.

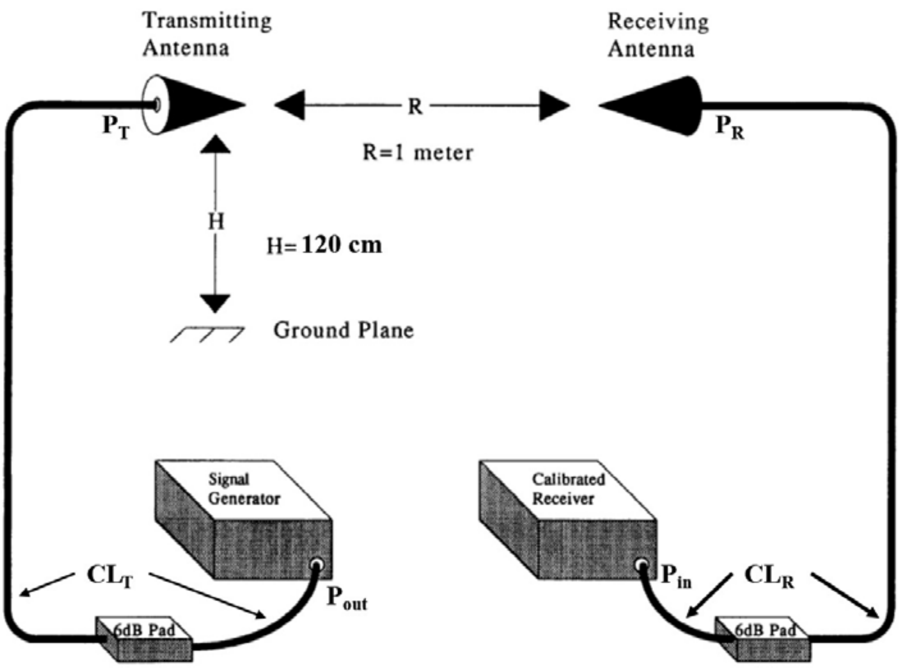


Figure 3.18: Test set-up for determining the 1m-gain utilising the two identical antenna (SAE 2003). This method takes advantage of the laws of antenna pattern reciprocity.

For a symmetrical radio frequency transmit/receive system as illustrated in Figure 3.18, an expression for the power driven into the input of the transmitting antenna can be written in terms of power measured at the 50 Ω output of the tracking generator, as in Equation 3.19. As well, a similar expression for the power seen at the receiving antenna output terminals can be written in terms of the power measured at the 50 Ω input of the spectrum analyser, as in Equation 3.20. These expressions can be simply written in terms of dBs for any given frequency point on the swept spectrum.

$$P_T\,(dBm) = P_{out}\,(dBm) - CL_T\,(dB) \tag{3.19}$$

and

$$P_R\,(dBm) = P_{in}\,(dBm) + CL_R\,(dB) \tag{3.20}$$

Where:

P_T is the power presented to terminals of the transmitting antenna in dBm,

P_R is the power driven by the terminals of the receiving antenna in dBm,

P_{out} is the power driven out of the tracking generator's 50 Ω output in dBm,

P_{in} is the power measured at the spectrum analyser's 50 Ω output in dBm,

and $CL_T = CL_R$ is the cable loss in dB, including the 6 dB Attenuator (identical to both sides).

From Friis Transmission Formula as in Equation 2.14, an simpler expression can be written in dBs.

$$P_R\,(dBm) = P_T\,(dBm) + G_T\,(dB) + G_R\,(dB) + 20LOG\left(\frac{\lambda}{4\pi r}\right)(dB) \tag{3.21}$$

Where:

G_T is the gain of the transmitting antenna in dB,

G_R is the gain of the receiving antenna in dB,

λ is the wavelength of any point on the swept spectrum in metres, and

r is the distance between the transmitting and receiving antennas in metres.

Since the configuration of Figure 3.18 is symmetrical and $r = 1$ m, Equation 3.21, $G_T = G_R = 2G$ and may be re-written as an expression for the insertion loss of the antenna system.

$$P_R\,(dBm) - P_T\,(dBm) = 2G\,(dB) + 20LOG\left(\frac{c}{4\pi}\right)(dB) - 20LOG\,(f)\,(dB) \tag{3.22}$$

Where:

c is the velocity of light in space, 3×10^8 metres per second, and

f is the frequency at any point on the swept spectrum in hertz.

Substituting Equations 3.19 and 3.20 into Equation 3.22

$$P_{in}\ (dBm) + CL_R\ (dB) - P_{out}\ (dBm) + CL_T\ (dB) = 2G\ (dB) + 147.6\ (dB) - 20LOG\,(f)\ (dB) \tag{3.23}$$

Since $CL_R = CL_T$, condensing and rearranging Equation 3.23, an expression for individual antenna gain, G in dB is written

$$G\ (dB) = \frac{P_{in} - P_{out} + 2CL - 147.6 + 20LOG\,(f)}{2}\ (dB) \tag{3.24}$$

Where insertion loss, $P_{out} - P_{in}$ in dBm and f are read off the spectrum analyser and CL is provided from a separate insertion loss measurement, bypassing the two-antenna system. To find $P_{in} - P_{out}$, change the sign of the measured insertion loss.

According to Kraus (Kraus 1988), the effective height, h_{eff}, of an antenna may be defined as the ratio of the voltage, V_o, at its terminals to the incident electric field, E, in which the antenna is located.

Thus,

$$h_{eff} = \frac{V_o}{E} \tag{3.25}$$

Where:

h_{eff} is in metres,

V_o is in volts, and

E is in volts per meter

However, if the antenna is terminated correctly in its output impedance, its output voltage will be halved.

$$V_o = \frac{h_{eff}E}{2} \tag{3.26}$$

Further, Kraus states that

$$h_{eff} = 2\sqrt{\frac{A_{em}R_r}{Z}} \tag{3.27}$$

and that

$$A_{em} = \frac{{h_{eff}}^2 Z}{4R_r} \tag{3.28}$$

Where:

A_{em} is the maximum effective aperture in metres squared,

R_r is the antenna's radiation resistance matched to its load in ohms, and

Z is the intrinsic impedance of free space (377 Ω).

Therefore, effective height and effective aperture are related to radiation resistance and the intrinsic impedance of space (Kraus 1988). Kraus goes on to show that there is an important relationship between the effective aperture and the directivity of and antenna (Kraus 1988).

$$D = \frac{4\pi}{\lambda^2} A_{em} \tag{3.29}$$

Where:

D is the directivity of the antenna (dimensionless), and

λ is the wavelength in metres.

Substituting Equation 3.29 into Equation 3.27:

$$h_{eff} = \lambda\sqrt{\frac{DR_r}{\pi Z}} \tag{3.30}$$

Referring to an isotropic source, the antenna gain is related to directivity by an efficiency factor.

$$G = kD \tag{3.31}$$

Where:

> k is the dimensionless efficiency factor of the antenna ($0 \leq k \leq 1$), and
>
> G is the numeric power gain.

Substituting Equation 3.30 into Equation 3.26, assuming that $G = D$ for an ideally isotropic antenna, and a nominal 50Ω system where any mismatches are insignificant.

$$V_o = \frac{E\lambda}{2}\sqrt{\frac{GR_r}{\pi Z}} = \frac{E\lambda}{2}\sqrt{\frac{G50\ \Omega}{\pi 377\ \Omega}} = E\frac{\lambda}{9.73}\sqrt{G} \tag{3.32}$$

Rearranging Equation 3.32, to convert the voltage measured at the terminals of an antenna connected into a matched 50 Ω receiver into the electric field strength incident at the antenna.

$$E = \frac{9.73}{\lambda\sqrt{G}}V_o \tag{3.33}$$

Therefore, the numeric Antenna Factor, AF, to convert volts into volts per metre is

$$AF = \frac{9.73}{\lambda\sqrt{G}} \tag{3.34}$$

Re-writing Equation 3.34 in dBs, utilising the antenna gain $G\ \ (dB)$ as derived in Equation 3.24.

$$AF\ \ (dB) = 20LOG\,(f) - 149.8 - G\ \ (dB) \tag{3.35}$$

The appropriate antenna factor is then added to the voltage at the spectrum analyser input which is indicated in decibels with respect to 1 μV, along with cable-loss, attenuator and other loss factors to obtain field intensity in decibels with respect to 1 μV/m.

$$E\ \ (dB\mu V/m) = V\ \ (dB\mu V) + AF\ \ (dB) + CableLoss\ \ (dB) + OtherLoss\ \ (dB) \tag{3.36}$$

A separate AF table will be required for vertical and horizontal polarisation, which will be required for the biconical and log-periodic antennas identified above. As a minimum, AF figures should be determined at frequency increments of at least one tenth of a decade, as shown in Table 3.6.

Frequency Range	Frequency Increment
30 MHz - 100 MHz	10 MHz
100 MHz - 1GHz	100 MHz

Table 3.6: Minimum calibration intervals for the higher frequency electric field antennas

3.3.8 Sensor verification

After calibration, the most critical task required to be undertaken is a verification that each sensor is actually capable of reasonably accurately measuring the emissions of the EUT. This verification is based on the simple principle that if a known signal, conducted or radiated, is injected into the respective sensor systems, measurement and application of the established calibration factors, should provide close to the value of the injected signal. MIL-STD-461G typically applies ± 3 dB as an acceptable margin of error for formal testing. Figure 3.19 illustrates this general process.

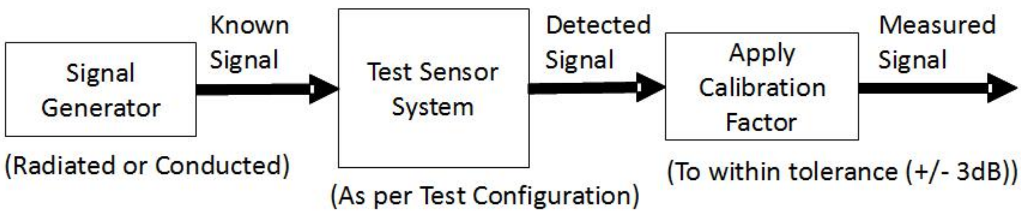


Figure 3.19: General Verification Process

The intention of this verification step is to provide confidence that the sensors are actually capable of properly detecting EMI with reasonable accuracy. As the intention of pre-compliance testing is to find any significant emissions of concern, absolute accuracy is not required.

3.3.9 Pre-compliance Test Protocol

The high-level protocol for each of the EMI measurements of interest is generally based on the same procedure.

Most test procedures will require a scan of the ambient conditions prior to a live measurement of an energised EUT. Since there are no controls over the amount and repetition rate of background noise as there is no screened environment, it was necessary to activate the Peak-hold function of the spectrum analyser for an arbitrarily extended period (say 30 seconds) in order to capture any local switching or other infrequent noise likely to be present during a live measurement.

The following framework holds true for both conducted or radiated emissions:

1. Understand any specific peculiarities of the EUT (such as safety earth points, physical size and shape, ventilation clearances, etc),
2. Collect the equipment, cables and accessories required for the specific test to be performed,
3. Check for any damage and the serviceability of individual items,
4. Configuration of the respective test setup, including the ground plane arrangement, with specific treatment of the safety earth scheme, making sure that highest priority is safety,
5. Activate the EUT and the test equipment and allow it to boot, warm-up, or otherwise stabilise,
6. Configure test equipment settings such as frequencies, RBW, data storage, etc,
7. Undertake a simple verification of the sensor system to determine that the system is functional,
8. Where necessary, take an ambient reading (with the EUT turned off) to verify that there are major interfering signals from elsewhere and determine that testing is viable under these ambient conditions,
9. Undertake actual test scans and capture the data as well as noting file names and any other points of interest such as if the facility temperature was particularly cold or warm, noticeable humidity or dryness, nearby activities that might impinge or results, etc.
10. Verify that all required data is captured prior to shutting down and dismantling the test setup.

While each facility and even each EUT will probably require some special treatment due to specific unforeseen peculiarities, the key elements are safety and being able to determine if the EUT emits EMI of a significant level. As previously discussed in the preamble of Section 3.3, there is a lot of flexibility that can be allowed for pre-compliance testing.

3.4 Summary of Methodologies

This chapter has detailed the methodologies that were used in both the development of the gap analysis of Chapter 4 and the pre-compliance test protocol design of Chapter 5. This chapter has drawn on the theoretical information and facts gathered in the latter sections of the literature review of Chapter 2 and applied them to the specific needs of the gap analysis and the pre-compliance test design. In many cases this information was further developed in detail for the particular requirements of these areas.

A complete framework was established for the gap analysis. This covered the identification of EMI standards for comparison, determination of the criteria for that comparison, required adjustments and scaling between the corresponding criteria and a general procedure for the presentation of results.

Similarly, a comprehensive structure was presented for the methodical development of the pre-compliance test design. A thorough explanation of the basic facilities and the common hardware items required in order to reasonably approximate both conducted and radiated emissions tests as detailed in MIL-STD-461G. Further, a detailed description of the specific hardware sensors and their methods of operation was provided. In some cases, considerable development of the basic theory provided in Chapter 2 was undertaken to provide the basis for the calibration of the respective sensor systems.

A general high-level procedure was presented upon which the detailed test protocols for a specific facility, test equipment and EUT may be developed.

General guidance for sensor system verification was also presented in order to provide the basis to prove that the sensors can be used for pre-compliance testing with reasonable confidence of their accuracy.

Chapter 4

Gap Analysis

4.1 Overview

As discussed in Section 3.2.1, this Gap Analysis critically investigates the level of compliance of the selected two main commercial standards to the selected MIL-STD-461G requirements for both conducted and radiated emissions.

Both the CISPR and FCC standards identified in Section 3.2.1, reference CISPR measurement guidelines as specified in CISPR 16-1-1. The FCC standard also identifies ANSI C63.4-2014, which is very similar and identifies that either specification is acceptable and therefore equivalent. Each specification identifies a set of frequency bands and associated measurement parameters such as minimum RBW and Detector types for test measurements.

As it has been determined that both standards agree with the CISPR 16-1-1 definition, for simplicity, the following will only refer to the these CISPR measurement guidelines. Table 4.1 shows the five main CISPR frequency bands and corresponding measurement parameters which are common to both conducted and radiated test measurements. It should be reinforced here that these guidelines cover the entire spectrum of CISPR interest and the above identified standards for ITE only refers to parts of this spectrum, as will be seen in the following sections.

This Gap Analysis incorporates a comparison of the corresponding detailed criteria as identified in Section 3.2.2, and presents the resulting detailed sub-analyses as defined in

Section 3.2.3.

4.1.1 Common Measurement Instrument Parameters

The following measurement instrument parameters, as seen in Table 4.1, are specified for CISPR testing as per CISPR 16-1-1 and are common to both CISPR 22 and 32(ITE) as well as to FCC Part 15 Subpart B. It should be noted that both MIL-STD-461G and CISPR-1-1 require a Gaussian IF-filter shape with a 6dB form-factor. These parameters are explained in some detail in Section 2.5.2.1

CISPR Band	**Frequency Span**	**RBW**	**Detector**
A	9 kHz to 150 kHz	200 Hz	Quasi-Peak or Average
B	150 kHz to 30 MHz	9 kHz	Quasi-Peak or Average
C	30 MHz to 300 MHz	120 kHz	Quasi-Peak or Average
D	300 MHz to 1 GHz	120 Hz	Quasi-Peak or Average
E	1 GHz to 18 GHz	1 MHz	Peak or Average

Table 4.1: Common Resolution Bandwidths for commercial EMC standards

In comparison with the MIL-STD-461G requirements' measurement instrument settings as summarised in Table 2.7, CISPR and FCC settings for RBW either meet or exceed the MIL-STD-461G requirements, except for most of the lower range between 9kHz and 30MHz as summarised in Table 4.2.

Frequency Span	MIL-STD-461G RBW	CISPR/FCC RBW	Compliance
30 Hz to 1 kHz	10 Hz	No Coverage	Non-Compliant
1 kHz to 9 kHz	100 Hz	No Coverage	Non-Compliant
9 kH to 10 kHz	100 Hz	200 Hz	Exceeds
10 kHz to 150 kHz	1 kHz	200 Hz	Non-Compliant
150 kHz to 10 MHz	10 kHz	9 kHz	Non-Compliant
10 MHz to 30 MHz	10 kHz	9 kHz	Non-Compliant
30 MHz to 1 GHz	100 kHz	120 kHz	Exceeds
1 GHz to 18 GHz	1 MHz	1 MHz	Compliant

Table 4.2: Comparison of RBW settings specified by CISPR/FCC against MIL-STD-461G requirements

4.1.2 Common Test Set-up

Generally, both CISPR and FCC test standards specify a 50 μH/50 Ω LISN be applied between the AC mains power supply and the EUT on both the active and the neutral return of the power lines. As well, both specify the use of a ground plane. While there are other individual specifics of test setups for both conducted and radiated emissions test measurements, these are common to all test configurations. Although not exactly the same arrangements as specified by MIL-STD-461G, discussed in Section 2.4.3, these test set-up configurations are generally analogous in many ways and are intended to provide similar, consistent, reproducible controls for the measurement of emissions and, hence, reproducibility of the measurements.

4.2 Gap Analysis of Conducted Emissions standards

Table 4.3 shows the basic limits for conducted emissions associated with CISPR 22 and 32(ITE). In the case of conducted emissions, the limits specified in FCC Part 15 Subpart B are identical to those specified in the CISPR standards.

CISPR 22 / 32(ITE) and FCC Part 15 Subpart B	Class A Limits			Class B Limits		
Conducted Emissions Frequency Span	QP (dBμV)	AV (dBμV)	PK (dBμV)	QP (dBμV)	AV (dBμV)	PK (dBμV)
150kHz to 500kHz	79	66		66-56	56-46	
500kHz to 5MHz	73	60		56	46	
5MHz to 30MHz	73	60		60	50	

Table 4.3: CISPR 22/32(ITE) and FCC Part 15 Subpart B conducted emissions limits

4.2.1 Frequency Coverage comparison with MIL-STD-461G

The immediately obvious differences, as shown in Figure 4.1, when compared to MIL-STD-461G conducted emissions requirements of CE101 and CE102, is that the frequency coverage of the commercial standards does not comply with CE101 at all and that they can only partially comply with CE102 from 150 kHz. This leaves a gap between 10 kHz and 150 kHz. It should be noted that this is the typical switching frequency range of much of the switch mode power supply technology present in most COTS ICT equipment. Hence, it does indicate a risk of a potential non-compliance and would require further investigation prior to completion of any design intended to meet CE102.

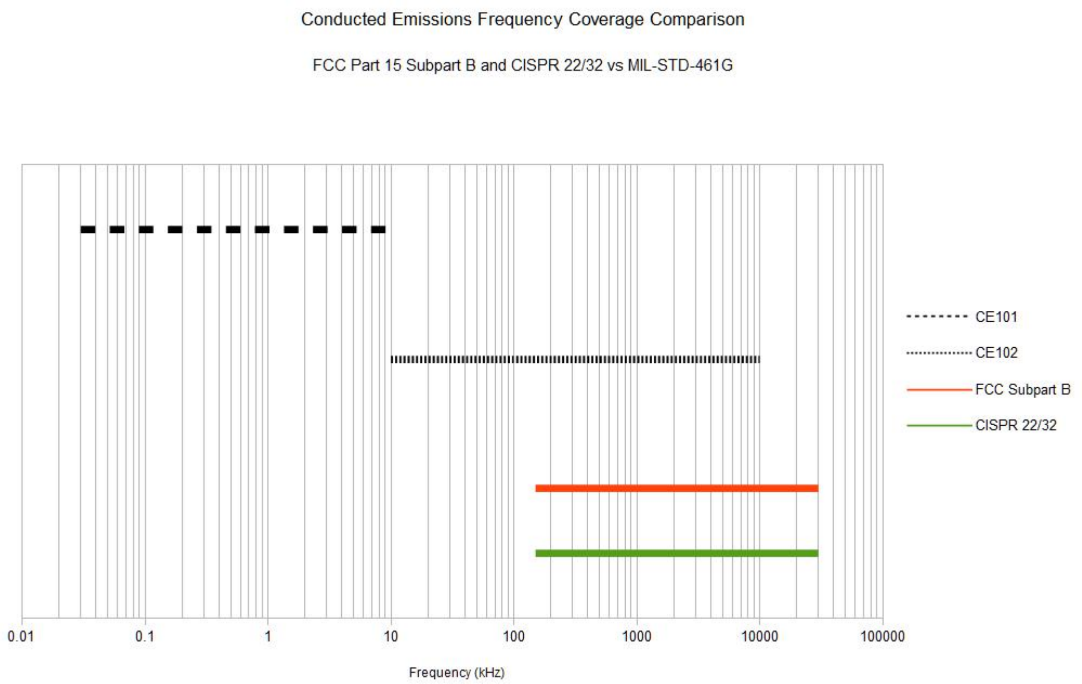


Figure 4.1: Comparison of frequency coverage of CISPR 22/32(ITE) and FCC Part 15 Subpart B conducted emissions limits with MIL-STD-461G CE101 and CE102

4.2.2 Limit comparison with MIL-STD-461G

As described in Section 3.2.2.2, limits identified as quasi-peak or average values can be extrapolated as Peak values. As all MIL-STD-461G limits are stated as peak levels, this adjustment should be made, as seen in Table 4.4, to allow a like for like comparison of commercial limits to those of the military standard.

CISPR 22 / 32(ITE) and FCC Part 15 Subpart B	Class A Limits		Class B Limits	
Conducted Emissions Frequency Span	Extrapolated PK based on QP Limit (dBμV)	PK (dBμV)	Extrapolated PK based on QP Limit (dBμV)	PK (dBμV)
150kHz to 500kHz	89		76-66	
500kHz to 5MHz	83		66	
5MHz to 30MHz	83		70	

Table 4.4: CISPR 22/32(ITE) and FCC Part 15 Subpart B conducted emissions limits as extrapolated peak values

As shown in Figure 4.2, the comparison of limits between the commercial standards and CE102, shows that Class A quasi-peak and average limits are higher than or similar to those of MIL-STD-461G. This indicates that in comparison with the peak limits of CE102, the corresponding extrapolated peak of a commercial Class A measurement would be higher than the CE102 peak limit. Therefore, commercial Class A conducted emissions standards are clearly non-compliant with MIL-STD-461G, requirement CE102.

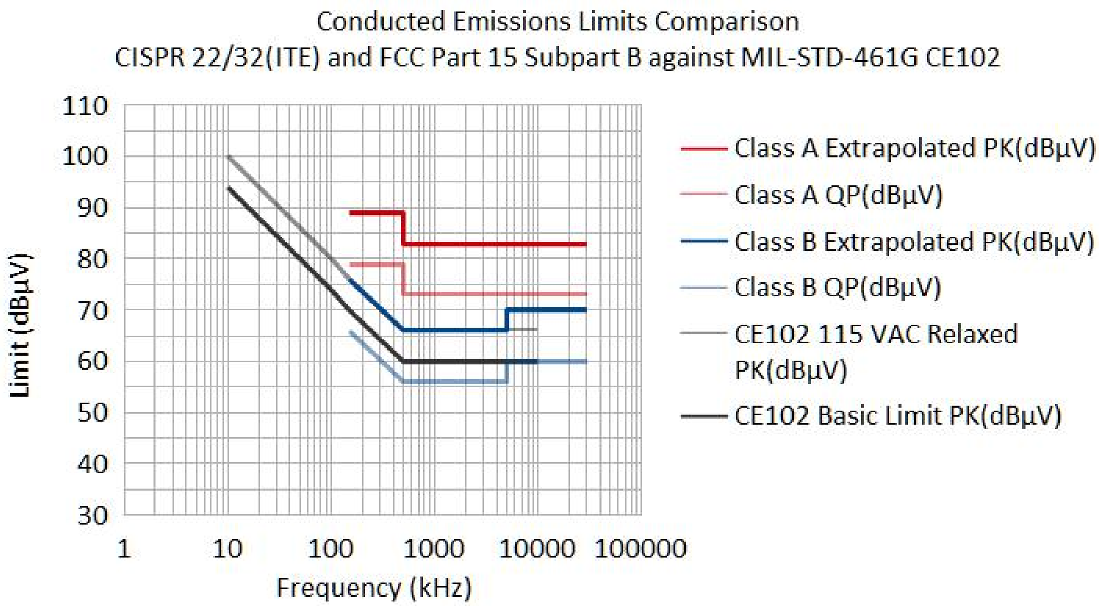


Figure 4.2: Comparison of CISPR 22/32(ITE) and FCC Part 15 Subpart B conducted emissions limits with MIL-STD-461G CE102

Further, as shown in Figure 4.2, the commercial Class B limits are the same or slightly lower than the CE102 limit for of the overlapping frequency range. Noting that an extrapolated peak compared to both the quasi-peak and average limits is higher than the CE102 peak limit, the commercial Class B conducted emissions standards are very likely to be non-compliant with MIL-STD-461G, requirement CE102.

4.2.3 Conducted Emissions Compliance Summary

It can be seen in Section 4.2.1 that there is no commercial EMC coverage of CE101 requirements. This must be considered a non-compliance against that MIL-STD-461G requirement.

Table 4.5, shows a summary compliance matrix of the identified conducted emissions against the CE102. While some areas of Figure 4.2 to be relatively close to compliance, close scrutiny of RBW and detector settings show that these limits are not able to be considered compliant.

Standard	Frequency Span	Frequency Span	Detector	RBW (6dB)	Limit (dBµV)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV)	Compliance	Comment
MIL-STD-461G CE102(115VAC) (Submarines)	10kHz-150kHz	150kHz-500kHz	Pk	10kHz	66	500kHz-5MHz	Pk	10kHz	66	5MHz-10MHz	Pk	10kHz	66		Baseline for comparison
CISPR22/32 (ITE) (Class A)	NIL	150kHz-500kHz	QP	9kHz	79	500kHz-5MHz	QP	9kHz	73	5MHz-10MHz	QP	9kHz	73	NON-COMPLIANT	RBW too narrow, QP Limits are non-compliant as they were significantly higher that the baseline, when extrapolated as a Peak Limit. No low frequency coverage.
CISPR22/32 (ITE) (Class B)	NIL	150kHz-500kHz	QP	9kHz	66-56	500kHz-5MHz	QP	9kHz	56	5MHz-10MHz	QP	9kHz	60	NON-COMPLIANT	RBW too narrow, QP Limits while the same as the baseline limit between 500kHz and 5MHz, they are non-compliant elsewhere in the frequency range as they were significantly higher that the baseline, when extrapolated as a Peak Limit. No low frequency coverage.
FCC Part 15 Subpart B (Class A)	NIL	150kHz-500kHz	QP	9kHz	79	500kHz-5MHz	QP	9kHz	73	5MHz-10MHz	QP	9kHz	73	NON-COMPLIANT	RBW too narrow, QP Limits are non-compliant as they were significantly higher that the baseline, when extrapolated as a Peak Limit. No low frequency coverage.
FCC Part 15 Subpart B (Class B)	NIL	150kHz-500kHz	QP	9kHz	66-56	500kHz-5MHz	QP	9kHz	56	5MHz-10MHz	QP	9kHz	60	NON-COMPLIANT	RBW too narrow, QP Limits while the same as the baseline limit between 500kHz and 5MHz, they are non-compliant elsewhere in the frequency range as they were significantly higher that the baseline, when extrapolated as a Peak Limit. No low frequency coverage.

Table 4.5: MIL-STD-461G compliance gap summary matrix for CISPR 22/32 and FCC Part 15 Subpart B conducted emissions

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4.3 Gap Analysis of Radiated Emissions standards

4.3.1 CISPR 22 and 32(ITE)

There is no equivalent CISPR 22 or 32(ITE) or corresponding limit that can be compared to MIL-STD-461G, requirement RE101. As such, the CISPR standards do not comply with RE101.

Table 4.6 shows the basic limits for radiated emissions associated with CISPR 22 and 32(ITE). In the case of radiated emissions, the limits specified under CISPR are somewhat different to FCC Part 15 Subpart B, which will be detailed later in this chapter.

CISPR 22 / 32(ITE)	Class A Limits			Class B Limits		
Frequency Span Radiated Emissions	QP (dBµV/m) (10m)	AV (dBµV/m) (3m)	Pk (dBµV/m) (3m)	QP (dBµV/m) (10m)	AV (dBµV/m) (3m)	Pk (dBµV/m) (3m)
30MHz to 230MHz	40			30		
230MHz to 1GHz	47			37		
1GHz to 3GHz		56	76		50	70
3GHz to 6GHz		60	80		54	74

Table 4.6: CISPR 22/32(ITE) radiated emissions limits

Of special note, the measurement distances for sub-1 GHz measurements are set at 10 m and the measurement distances for frequencies above 1 GHz are set at 3 m. These measurement distances virtually guarantee far-field operation during actual physical testing.

4.3.1.1 Frequency Coverage comparison with MIL-STD-461G

As shown in Figure 4.3, when compared to MIL-STD-461G radiated emissions requirements of RE102, the frequency coverage of the CISPR standards only partially complies with RE102 from 30 MHz to 6 GHz. This leaves a gap between 10 kHz and 30 MHz as well as a gap between 6 GHz and 18 GHz.

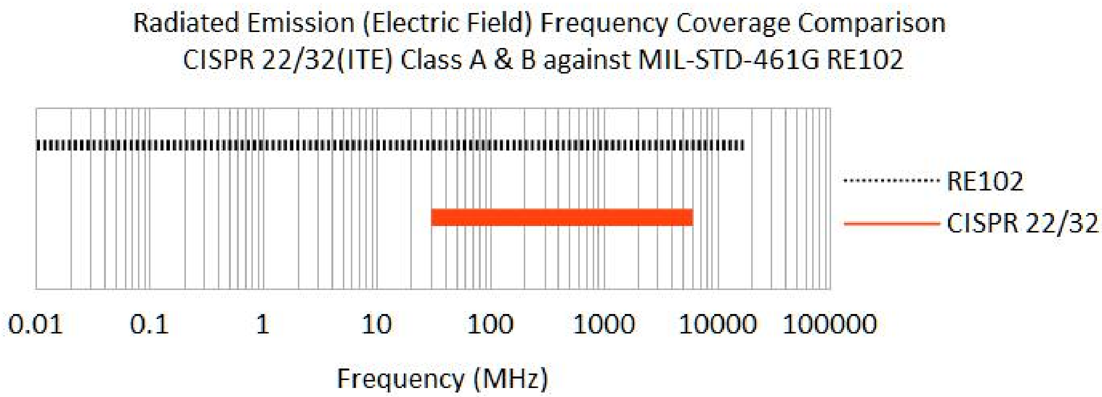

Figure 4.3: Comparison of frequency coverage of CISPR 22/32(ITE) radiated emissions limits with MIL-STD-461G RE102

4.3.1.2 Limits Adjusted to a 1 m Measurement Distance

Using the formula for determining the linear distance extrapolation described in Section 3.2.2.1, the following extrapolations were found to adjust both 10 m and 3 m limits to 1 m as required for comparison to MIL-STD-461G Limits.

CISPR 22 / 32(ITE)	Class A (adjusted to 1m) Limits			Class B (adjusted to 1m) Limits		
Frequency Span Radiated Emissions	QP (dBμV/m)	AV (dBμV/m)	Pk (dBμV/m)	QP (dBμV/m)	AV (dBμV/m)	Pk (dBμV/m)
30MHz to 230MHz	60			50		
230MHz to 1GHz	67			57		
1GHz to 3GHz		65.5	85.5		59.5	79.5
3GHz to 6GHz		69.5	89.5		63.5	83.5

Table 4.7: CISPR 22/32(ITE) limits adjusted to 1 m

4.3.1.3 Limit Comparisons with MIL-STD-461G

As described in Section 3.2.2.2, limits identified as quasi-peak or average values can be extrapolated as Peak values. As all MIL-STD-461G limits are stated as peak levels, this adjustment should be made, as seen in Table 4.8, to allow a like for like comparison of commercial limits to those of the military standard.

CISPR 22 / 32(ITE)	Class A (adjusted to 1m) Limits		Class B (adjusted to 1m) Limits	
Frequency Span Radiated Emissions	Extrapolated Peak based on QP (dBμV/m)	Pk (dBμV/m)	Extrapolated Peak based on QP (dBμV/m)	Pk (dBμV/m)
30MHz to 230MHz	70		60	
230MHz to 1GHz	77		67	
1GHz to 3GHz		85.5		79.5
3GHz to 6GHz		89.5		83.5

Table 4.8: CISPR 22/32(ITE) radiated emissions limits as extrapolated peak values

As shown in Figure 4.4, the comparison of limits between the CISPR standards and RE102, shows that Class A quasi-peak limits between 30 MHz and 1 GHz and average limits are higher than or similar to those of RE102 peak limit. From 1 GHz to 6 GHz, the Class A peak limit is well above the RE102 peak limit.

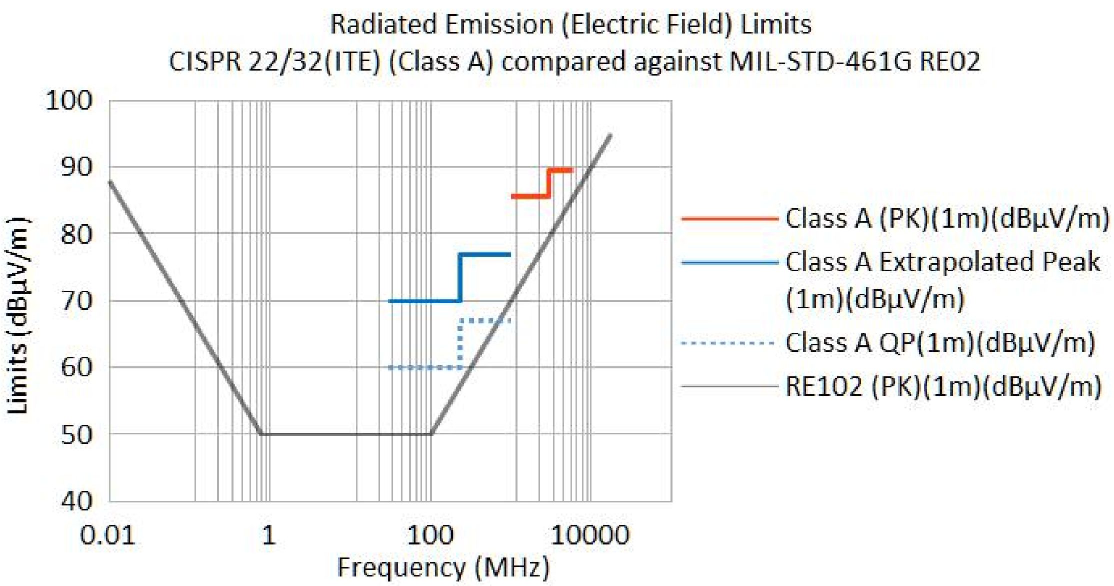

Figure 4.4: Comparison of CISPR 22/32(ITE) radiated emissions Class A limits with MIL-STD-461G RE102

This indicates that in comparison with the peak limits of RE102, CISPR Class A limits would be higher than the RE102 peak limit. Therefore, CISPR Class A radiated emissions standards are clearly non-compliant with MIL-STD-461G, requirement RE102.

Further, as shown in Figure 4.5, the CISPR Class B limits are the same or slightly lower than the CE102 limit for of the overlapping frequency range. Noting that an extrapolated peak compared to both the quasi-peak and average limits is likely to be higher than the CE102 peak limit, the CISPR Class B radiated emissions standards are very likely to be non-compliant with MIL-STD-461G, requirement CE102.

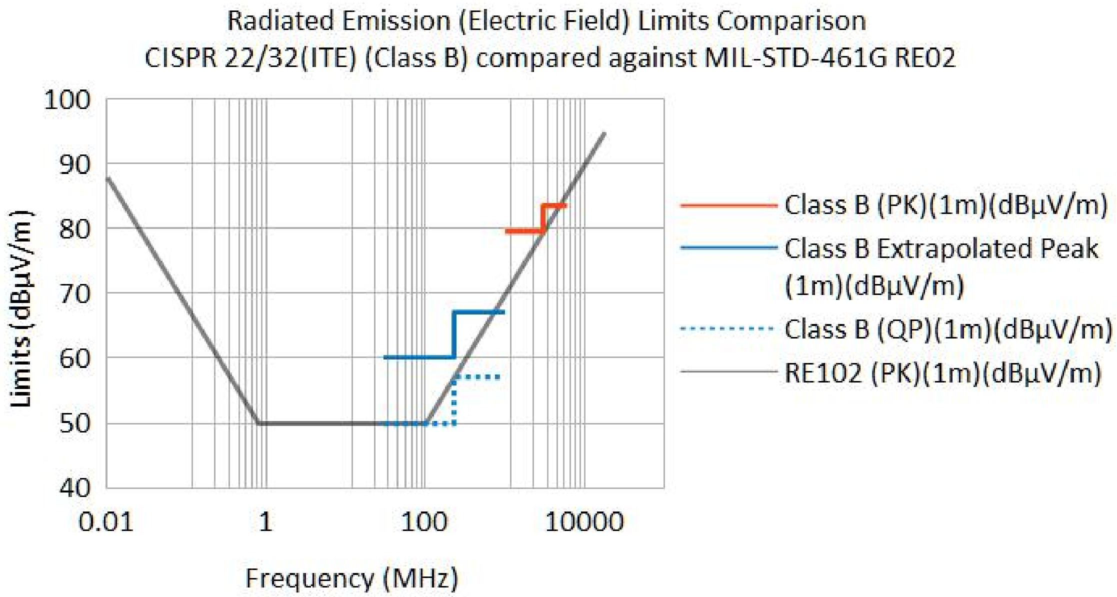

Figure 4.5: Comparison of CISPR 22/32(ITE) radiated emissions Class B limits with MIL-STD-461G RE102

4.3.1.4 CISPR 22/32(ITE) Radiated Emissions Compliance Summary

It can be seen in Section **??** that there is no CISPR coverage of RE101 and as such must be considered non-compliant against that MIL-STD-461G requirement.

Table 4.9, shows a summary compliance matrix of the identified CISPR 22 and 32(ITE) radiated emissions limits against the RE102. While some areas of the CISPR Class B limits seen Figure 4.5 seem to be relatively close to compliance, close scrutiny of coverage and detector settings show that these limits are not able to be considered compliant.

Standard	Frequency Span	Frequency Span	Detector	RBW (6dB)	Limit (dBμV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBμV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBμV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBμV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBμV/m)	Frequency Span	Compliance	Comment
MIL-STD-461G RE102(115VAC) (Submarines)	10kHz-30MHz	30MHz-100MHz	Pk	100kHz	50	100MHz-230MHz	Pk	100kHz	50-58	230MHz-1GHz	Pk	100kHz	58-70	1GHz-3GHz	Pk	1MHz	70-80	3GHz-6GHz	Pk	1MHz	80-86	6GHz-18GHz		Baseline for Comparison
CISPR22/32 (ITE)(Class A)	NIL	30MHz-100MHz	QP	120kHz	60	100MHz-230MHz	QP	120kHz	60	230MHz-1GHz	QP	120kHz	67	1GHz-3GHz	Pk	1MHz	85.5	3GHz-6GHz	Pk	1MHz	89.5	NIL	NON-COMPLIANT	Incomplete frequency span coverage. Extrapolated Peak valuse are consistently higher than the baseline RE102 limit in sections. Above 1GHz, the level is well above the RE102 limit.
CISPR22/32 (ITE)(Class B)	NIL	30MHz-100MHz	QP	120kHz	50	100MHz-230MHz	QP	120kHz	50	230MHz-1GHz	QP	120kHz	57	1GHz-3GHz	Pk	1MHz	79.5	3GHz-6GHz	Pk	1MHz	84.5	NIL	NON-COMPLIANT	Incomplete frequency span coverage. Extrapolated Peak valuse are consistently higher than the baseline RE102 limit in sections.

Table 4.9: Compliance gap summary matrix for CISPR 22/32 against MIL-STD-461G radiated emissions

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4.3.2 FCC Part 15 Subpart B (Unintentional Radiators)

There is no equivalent FCC Part 15 Subpart B or corresponding limit that can be compared to MIL-STD-461G, requirement RE101. As such, the FCC standards do not comply with RE101.

Table 4.10 shows the basic limits for radiated emissions associated with FCC Part 15 Subpart B.

FCC Part 15 Subpart B	Class A (10m) Limits			Class B (3m) Limits		
Frequency Span Unintentional Radiators	QP (dBμV/m)	AV (dBμV/m)	PK (dBμV/m)	QP (dBμV/m)	AV (dBμV/m)	PK (dBμV/m)
30MHz to 88MHz	39			40		
88MHz to 216MHz	43.5			43.5		
216MHz to 960MHz	46.5			46		
960MHz to 18GHz		49.5	69.5		54	74

Table 4.10: FCC Part 15 Subpart B radiated emissions limits

Of special note, the measurement distances for sub-1 GHz measurements are set at 10 m and the measurement distances for frequencies above 1 GHz are set at 3 m. These measurement distances virtually guarantee far-field operation during actual physical testing.

4.3.2.1 Frequency Coverage comparison with MIL-STD-461G

As shown in Figure 4.6, when compared to MIL-STD-461G radiated emissions requirements of RE102, the frequency coverage of the FCC requirements only partially comply with RE102 from 30 MHz to 18 GHz. This leaves a gap between 10 kHz and 30 MHz.

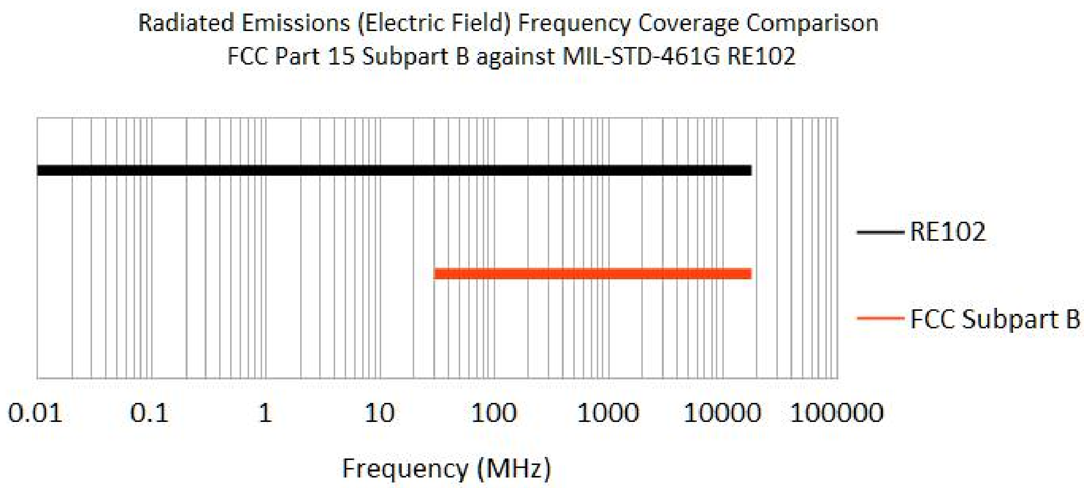

Figure 4.6: Comparison of frequency coverage of FCC Part 15 Subpart B radiated emissions limits against MIL-STD-461G RE102

4.3.2.2 Limits Adjusted to a 1 m Measurement Distance

Using the formula for determining the linear distance extrapolation described in Section 3.2.2.1, the following extrapolations, as seen in Table 4.11, were found to adjust both 10 m and 3 m limits to 1 m as required for comparison to MIL-STD-461G Limits.

FCC Part 15 Subpart B	Class A (adjusted to 1m) Limits			Class B (adjusted to 1m) Limits		
Frequency Span Unintentional Radiators	QP (dBμV/m)	AV (dBμV/m)	Pk (dBμV/m)	QP (dBμV/m)	AV (dBμV/m)	PK (dBμV/m)
30MHz to 88MHz	59			49.5		
88MHz to 216MHz	63.5			53		
216MHz to 960MHz	66.5			55.5		
960MHz to 18GHz		69.5	89.5		63.5	83.5

Table 4.11: FCC Part 15 Subpart B radiated emissions limits adjusted to 1 m

4.3.2.3 Limit comparisons with MIL-STD-461G

As described in Section 3.2.2.2, limits identified as quasi-peak or average values can be extrapolated as Peak values. As all MIL-STD-461G limits are stated as peak levels, this adjustment should be made, as seen in Table 4.8, to allow a like for like comparison of commercial limits to those of the military standard.

FCC Part 15 Subpart B	Class A (adjusted to 1m) Limits		Class B (adjusted to 1m) Limits	
Frequency Span Unintentional Radiators	Extrapolated PK based on QP Limit (dBµV/m)	Pk (dBµV/m)	Extrapolated PK based on QP Limit (dBµV/m)	PK (dBµV/m)
30MHz to 88MHz	69		59.5	
88MHz to 216MHz	73.5		63	
216MHz to 960MHz	76.5		65.5	
960MHz to 18GHz		89.5		83.5

Table 4.12: FCC Part 15 Subpart B radiated emissions limits as extrapolated peak values

As shown in Figure 4.7, the comparison of limits between the FCC standards and RE102, shows that Class A quasi-peak limits between 30 MHz and 1 GHz and average limits are higher than or similar to those of RE102 peak limit. From 1 GHz to 10 GHz, the Class A peak limit is above the RE102 peak limit.

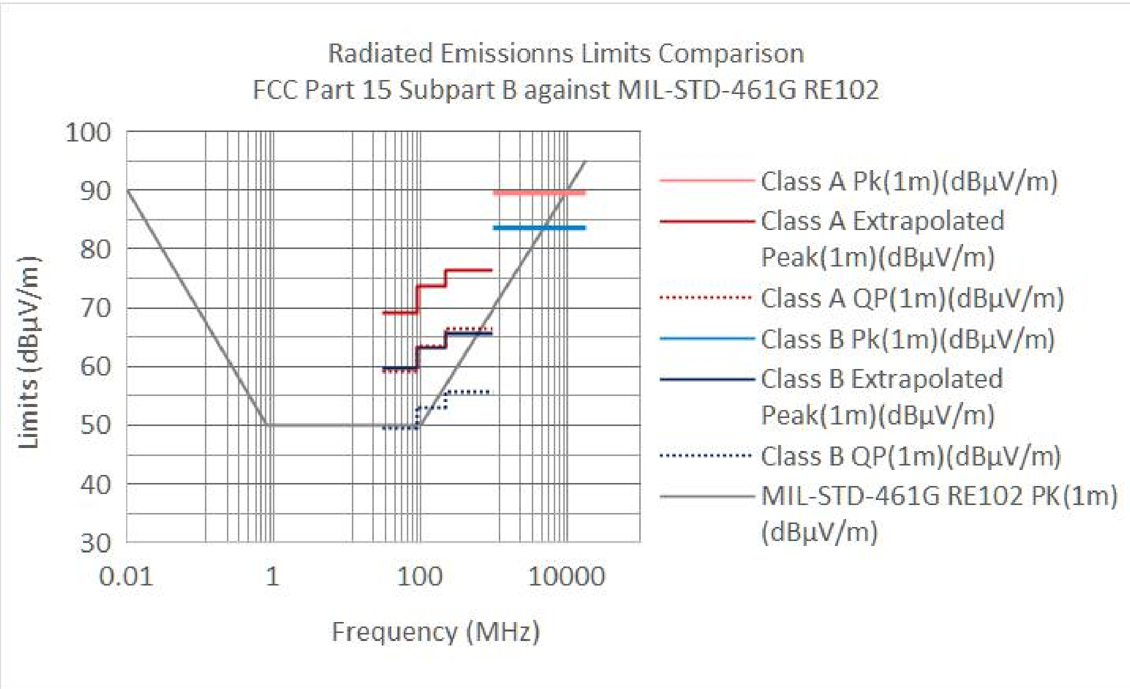

Figure 4.7: Comparison of FCC Part 15 Subpart B radiated emissions Class A and B limits against MIL-STD-461G RE102

This indicates that, in comparison with the peak limits of RE102, FCC Class A limits would be higher than the RE102 peak limit. Therefore, FCC Class A radiated emissions standards are clearly non-compliant with MIL-STD-461G, requirement RE102.

Further, as shown in Figure 4.7, the FCC Class B limits are the same or slightly lower than the RE102 limit of the overlapping frequency range. An extrapolated peak compared to both the quasi-peak and average limits is likely to be higher than the RE102 peak limit between 30 MHz and 1 GHz. The FCC Class B peak limit is higher than RE102 between 1 GHz and 5 GHz. While there are some areas of potential compliance, lack of coverage and areas of clear non-compliance must be summarised as FCC Class B limits to be non-compliant with MIL-STD-461G, requirement RE102.

4.3.2.4 FCC Part 15 Subpart B Radiated Emissions Compliance Summary

It can be seen in Section 4.3.2.1 that there is no FCC coverage of RE101 and as such must be considered non-compliant against that MIL-STD-461G requirement.

Table 4.13, shows a summary compliance matrix of the identified FCC Part 15 Subpart B Radiated Emissions Class A and B Limits against MIL-STD-461G, requirement RE102. While some areas of the FCC Class B limits seen Figure 4.7 seem to be relatively close to compliance, close scrutiny of coverage and detector settings and limit levels show that these limits are not able to be considered compliant with RE102.

Standard	Frequency Span	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Frequency Span	Detector	RBW (6dB)	Limit (dBµV/m)	Compliance	Comment
MIL-STD-461G RE102(115VAC)(Submarines)	10kHz-30MHz	30MHz-88MHz	Peak	100kHz	50	88MHz-100MHz	Peak	100kHz	50	100MHz-216MHz	Peak	100kHz	50-56	216MHz-960MHz	Peak	100kHz	56-69	960MHz-1GHz	Peak	1MHz	69-70	1GHz-18GHz	Peak	1MHz	70-95		Baseline for comparison
FCC Part 15 Subpart B (Class A)	NIL	30MHz-88MHz	Quasi-Peak	120kHz	59	88MHz-100MHz	Quasi-Peak	120kHz	63.5	100MHz-216MHz	Quasi-Peak	120kHz	63.5	216MHz-960MHz	Quasi-Peak	120kHz	66.5	960MHz-1GHz	Peak	1MHz	89.5	1GHz-18GHz	Peak	1MHz	89.5	NON-COMPLIANT	Extrapolated Peak Limits are consistently above RE 101 Peak Limits, No low Frequency Coverage. Minimal compliance above 10GHz.
FCC Part 15 Subpart B (Class B)	NIL	30MHz-88MHz	Quasi-Peak	120kHz	49.5	88MHz-100MHz	Quasi-Peak	120kHz	53	100MHz-216MHz	Quasi-Peak	120kHz	53	216MHz-960MHz	Quasi-Peak	120kHz	55.5	960MHz-1GHz	Peak	1MHz	79.5	1GHz-18GHz	Peak	1MHz	84.5	NON-COMPLIANT	Extrapolated Peak Limits are consistently above RE 101 Peak Limits, No low Frequency Coverage. Minimal compliance above 5GHz.

Table 4.13: Compliance gap summary matrix for FCC Part 15 Subpart B radiated emissions against MIL-STD-461G, requirement RE102

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4.4 Gap Analysis Conclusions

As shown in Table 4.14, a comparison of commercial standards based on CISPR 22 or 32 as well as FCC Part 15 Subpart B against MIL-STD-461G CE102 and RE102 has proven these commercial standards to be non-compliant. This comparison was facilitated with reasonable adjustments for translation of test measurement parameters. As well, these commercial EMI standards provide no coverage for CE101 Audio Frequency currents, nor is there any coverage for RE101 Magnetic Fields. Therefore, the general finding is non-compliance across the board.

MIL-STD-461G Requirement	**Standards based on CISPR 22 and 32(ITE)**	**FCC Part 15 Subpart B**	**Comment**
CE101	NON-COMPLIANT	NON-COMPLIANT	No coverage
CE102	NON-COMPLIANT	NON-COMPLIANT	Partial coverage and incompatible limits
RE101	NON-COMPLIANT	NON-COMPLIANT	No coverage
RE102	NON-COMPLIANT	NON-COMPLIANT	Partial coverage and incompatible limits

Table 4.14: Compliance Gap Analysis of CISPR/FCC against MIL-STD-461G requirements

There is a vast difference between the idea of the qualification of an individual piece of equipment with test report evidence to some standard; and the idea of compliance justification by simply reading one standard across to another. It is the latter idea to which this Gap Analysis pertains, as summarised in Table 4.14.

The actual COTS ICT equipment sought for insertion into a submarine combat system may well meet some or even all pertinent MIL-STD-461G requirements, but this cannot be surmised from such equipments' commercial certifications or qualifications. An appropriate course of action is to formally re-qualify such equipment to MIL-STD-461G. However, this would be an expensive exercise and such qualification tests may fail as this equipment was not specifically designed to pass them.

A more appropriate plan of action would be to undertake simpler and more practical pre-compliance testing to characterise the EMI performance of the COTS equipment with respect to MIL-STD-461G requirements. Such characterisation results, if non-compliant, can then be used by system designers to either seek other, better performing COTS equipment or provide measures in their system design to correct these non-compliances. Conversely, if the characterisation results show compliance, there would perhaps be no need to expend more effort.

Further to applying design measures, such as filtering, shielding or other means of EMI hardening the non-compliant COTS equipment, if the means of pre-compliance testing was readily available, inexpensive and quick to use, it can be applied at various stages throughout the design. By this monitoring of EMI performance throughout the design process, any emergent EMI problems can be dealt with as soon as possible in the design, prototyping and integration phases of this process.

Evidently, a need exists for a low-investment and practical pre-compliance test protocol to verify the EMI performance of such COTS equipment against the applicable military EMI standards, in the same way that designers must monitor power usage or heat dissipation.

Chapter 5

Pre-compliance Test Protocol Design

5.1 Overview

This chapter works through an example reference design, procurement and construction of the necessary facilities and equipment required for pre-compliance testing based on the methodology of Section 3.3. This is followed by the calibration process and MIL-STD-461G based verification measurements made to prove the correct operation of these items. As well, the development and rationale of simplified test sequences which, when combined, make up the proposed COTS pre-compliance test protocol for CE101, CE102, RE101 and RE102 measurements as required for internal submarine applications.

Any risks associated with the experimental content of this chapter have been previously analysed and the appropriate controls have been applied in accordance with the Hazard Risk Analysis of Appendix D.

5.2 General Test Set-up and Ancillary Equipment

The following are some of the general components and equipment that are required for both conducted and radiated emissions pre-compliance testing.

5.2.1 Ground Plane Design

The key technical parameters for the selection of Ground Plane material are conductivity and thickness, due to the skin effect (or depth of penetration), which is related to conductivity. Skin effect is especially important to radiated emissions testing.

Kraus and Fleisch show that the depth of penetration of the wavefront into a conductive surface, for a given frequency, is found with the following formula (Kraus & Fleisch 1999):

$$\delta = \frac{1}{\sqrt{f\pi\mu\sigma}} \tag{5.1}$$

Where:

δ is the depth of penetration in m,

f is the frequency of the wave in Hz,

μ is the permeability of free space ($4\pi \times 10^{-7}$ H/m), and

σ is the conductivity of the conductive surface in S/m.

The selection of ground plane material was based on the key criteria of availability, conductivity, cost and weight. The first metal that was researched was copper due to its excellent conductivity, as shown in Table 5.1. Aluminium was found to be almost as good a conductor, available, reasonably priced and relatively light. Unfortunately, copper was not in good supply, relatively heavy and very expensive. Stainless steel sheet was available, but more expensive than aluminium, was an order of magnitude poorer a conductor and quite heavy. Plain steel was not considered due to poor performance, heavy weight and its tendency to corrode rapidly in normal atmosphere.

Therefore, Aluminium was selected as the most practical ground plane material for this project.

Metal	Conductivity σ (S/m)
Annealed Copper	58.8×10^6
Aluminium	37×10^6
St. Steel 304	1.39×10^6

Table 5.1: Comparison of conductivity of various metals considered for Ground Plane construction (matweb.com).

The lowest frequency of interest to radiated electric field emissions is 10 kHz. Therefore, applying Equation 5.1, the maximum depth of penetration is about 1 mm. While a 1 mm thickness of Aluminium sheet was available, it was very sloppy and appeared to be easily damaged under-foot. Therefore, a slightly thicker 1.2 mm sheet was procured, which, while slightly more expensive, was obviously much more robust.

Figure 5.1: Resulting ground-plane configuration based on a limited number of aluminium sheets and available space.

While the guidance of MIL-STD-461G requires a minimum extension of the ground plane at least 2.5 m beyond the test equipment, this was neither practical due to space limitations, nor from a cost perspective. The extension of the ground plane was mostly limited to approximately 1.2 m. The general layout of the ground plane and the test table is shown in Figure 5.1.

The ground plane was coupled to the GPO safety earth by thick copper braid, clamped at several places. The ground plane was provided in several 800 mm $\times$ 1200 mm sheets, placed so that they were slightly overlapping as well as being clamped together with ground braid at several points.

5.2.2 Mains Power Supply Design

The mains power supply was limited to frequency of 50 Hz as supplied by household power GPOs. However, the voltage was down-converted from the nominal GPO 230 Vrms to approximately 115 Vrms with a 2000 VA, fused, variable Auto-transformer (or "Variac") and was also galvanically isolated from the mains with a 600 VA, fused, isolation transformer, which also incorporated and electrostatic shield. Hence, it was determined that the maximum load EUT that could be supported should not be more than about 500 W. Figure 5.2 shows the transformer combination used.

Figure 5.2: Mains power supply transformers. This image shows the 230 Vrms isolation transformer on the left which feeds the adjustable autotransformer (or "Variac") on the right, which is adjusted to 115 Vrms.

The output of the adjustable transformer drives the inputs of the LISNs.

5.2.3 LISN Design

Figure 5.3: Typical, commercially available, MIL-STD-461G compliant LISNs (com-power.com)

Referring to Section 3.3.5 and to Figure 2.17, it can be seen that the main element in each LISN is the 50 μH inductor. The rest of the components of this reference design are readily available to be procured from several sources. However, the inductor was not found to be available as an off the shelf supply.

The selection of the former for the inductor was the first step, as this would drive the shape and size of the inductor's basic form. It was found that there was a ready supply of 30 mm PVC pipe at hand, of 34 mm outer diameter. The wire for winding the inductor coil was selected from a limited variety of high quality enamelled copper wire. In the interests of future experimentation and EMI testing, it was determined that the LISN should be designed to handle a load current of at least 10 Arms. A wire diameter of 1.5 mm was selected as its maximum current handling was stated by the manufacturer as being 19 Arms, which provided an ample safety margin.

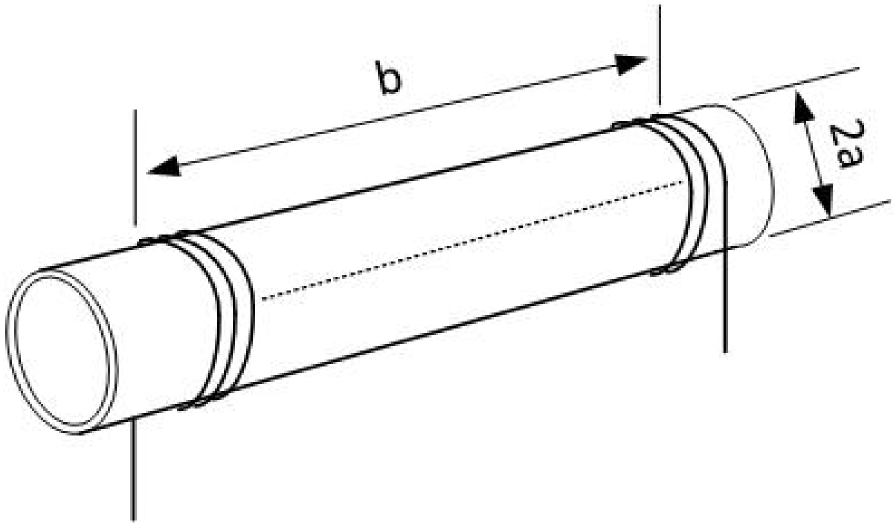

Figure 5.4: Diagrammatic view of the LISN inductor.

Grover shows that an approximate formula for the self-inductance of a long coil, as illustrated in Figure 5.4, is given as (Grover 1946):

$$L = 0.004\pi^2 a^2 b n_1^2 \tag{5.2}$$

Where:

L is the inductance of the coil in μH,

a is the mean radius of the former section in cm,

b is the length of the coil winding in cm, and

n_1 is the number of turns per cm for the given enamelled wire.

From the wire manufacturer's data, the 1.5 mm diameter wire, including the enamel thickness is 1.6 mm. This gives a value of $n_1 = 6.23$ turns per cm.

Rearranging Equation 5.2 to find b, the length of the coil was found to be 12.6 cm. The number of turns for the entire coil was determined to be 79 turns.

An inductor of these dimensions and turns was prototyped and found to provide slightly more than 50μH. Two turns were removed and measurement with an LCR meter showed that the inductance was almost exactly 50μH, as shown in Figure 5.5.

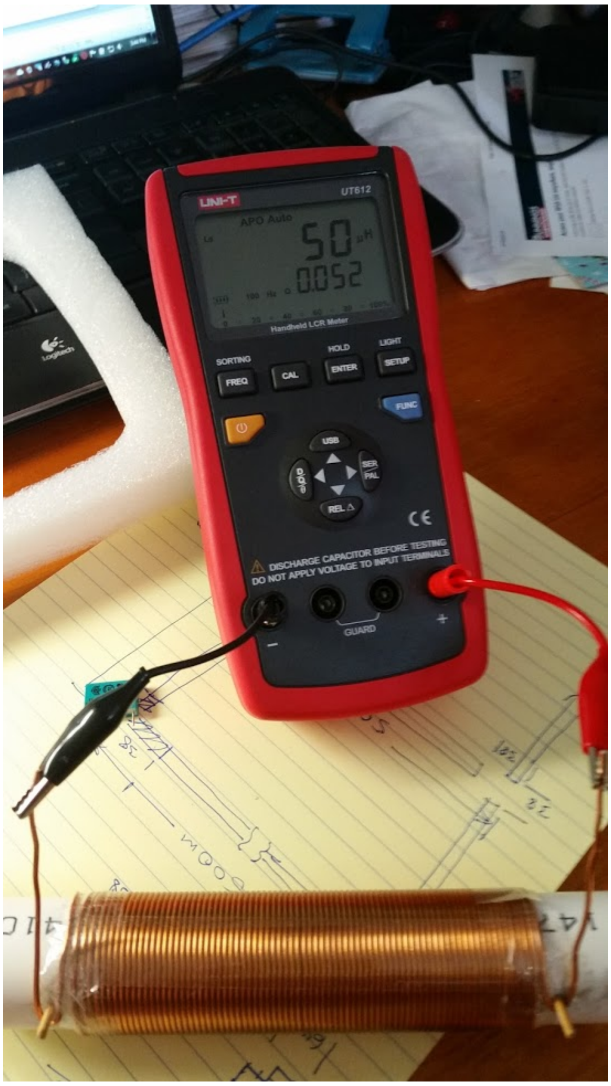

Figure 5.5: Hand-wound 50 μH inductors (on PVC pipe).

Therefore, the correct number of turns was determined to be 77. Two production inductors were then wound and measured to provide the correct inductance.

The LISN circuits, shown in Figure 5.6, were then constructed on solid copper-clad boards, observing good RF techniques such as minimal lead lengths and the use of wide copper braid rather than hook-up wire to minimise stray inductance. The component values were selected as per the reference design of Figure 2.17. The capacitors were selected as high-voltage mains-rated polyester types. The resistors were of a low-inductance type, encased in two-pin, TO-220 packages, which were screwed down to the board material to facilitate dissipation of any heat.

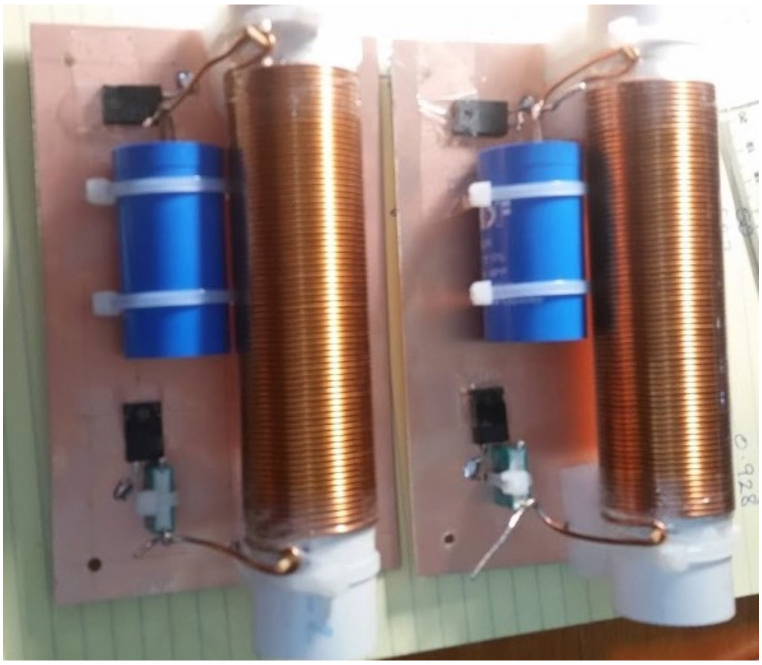

Figure 5.6: Completed LISN circuit card assemblies based on the MIL-STD-461G reference design.

The LISN circuits assemblies were then fitted and wired into drilled, die cast aluminium boxes. As shown in Figure 5.7, the boxes provide M8 ground studs at both the input and out ends. The input and output connectors were selected as 4 mm safety-shrouded banana-style sockets. The output sides have measurement ports terminated to BNC female sockets.

Figure 5.7: Completed, hand-made, MIL-STD-461G compliant LISN (output side shown)

Each LISN was tested for proper insertion loss as per the guidance of SAE AIR6236, as detalied in Section 3.3.5 and the test configuration of Figure 3.10. The results of both LISNs were identical and are illustrated in Figure 5.8, which are in compliance with the requirements of Figure 3.9.

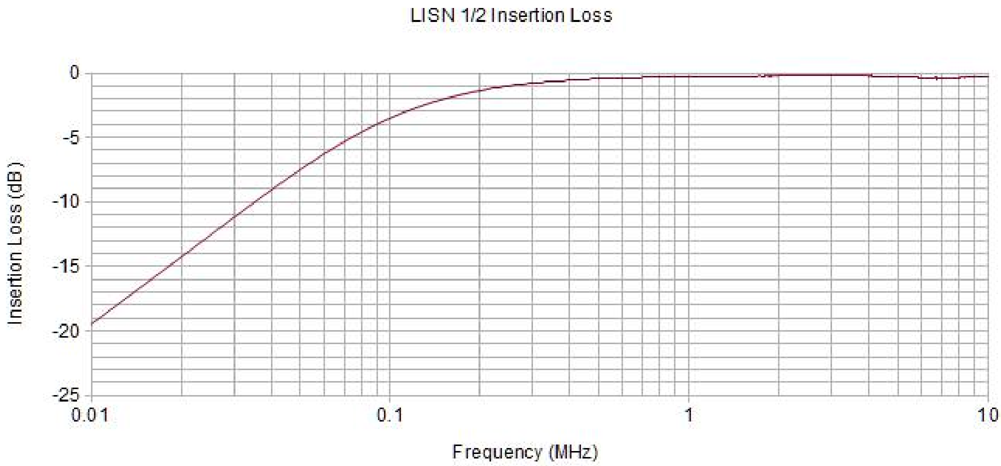

Figure 5.8: Measured insertion loss matches requirements of SAE AIR6236 (the measurements of both LISNs were virtually identical)

5.2.4 Interconnection and Measurement Cabling Design

There are two main types of cabling used in the configuration of this pre-compliance testing setup:

- Power reticulation cabling, and
- Signal cabling.

The default MIL-STD-461G guidance for power reticulation is to use unshielded power cables to and from the LISNs and to run them across the front of the test table, 5cm above the tables ground plane, as illustrated in Figure 3.4. However, Appendix A of MIL-STD-461G, states that the power cabling should be as per the final target installation, which would always be screened for internal submarine cabling. Noting that an RF-quiet screened room arrangement is not available, it was decided that power to the LISNs' input and from the LISNs' output would be screened and bonded to the LISNs' ground stud as shown in Figure 5.25, effectively bonding the screens to test setup's ground point.

As these power cables have either moulded plastic IEC-C13 or a moulded plastic NEMA 5-15 (Type B) plug at one end, the screen is only terminated at one end (at the LISN) and the screen is pulled up as far as possible at the plastic end, as shown in Figure 5.9.

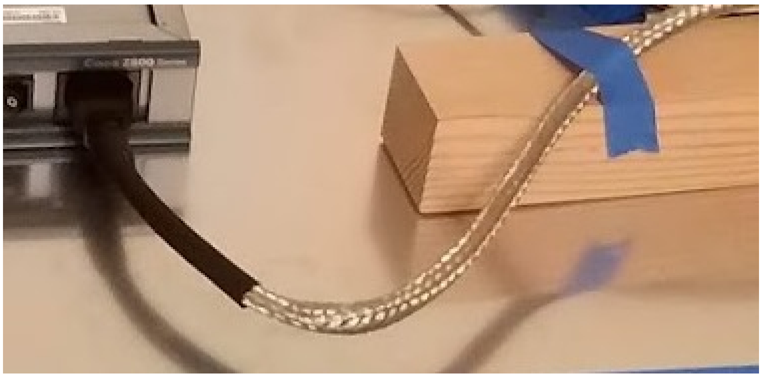

Figure 5.9: Overall screen pulled up as far as possible near the moulded plastic connector and held in place by adhesive heatshrink tubing.

The signal cabling is almost all relatively cheap, 50 Ω RG-58 coaxial cabling, terminated either end with cheap BNC male crimped plugs. The longest of these cables are 10 m in length, used for connection to sensors and antennas. As it was expected that these cables would have an appreciable insertion loss, especially at the higher frequencies of interest, a measurement was taken and the results are shown in Figure 5.10.

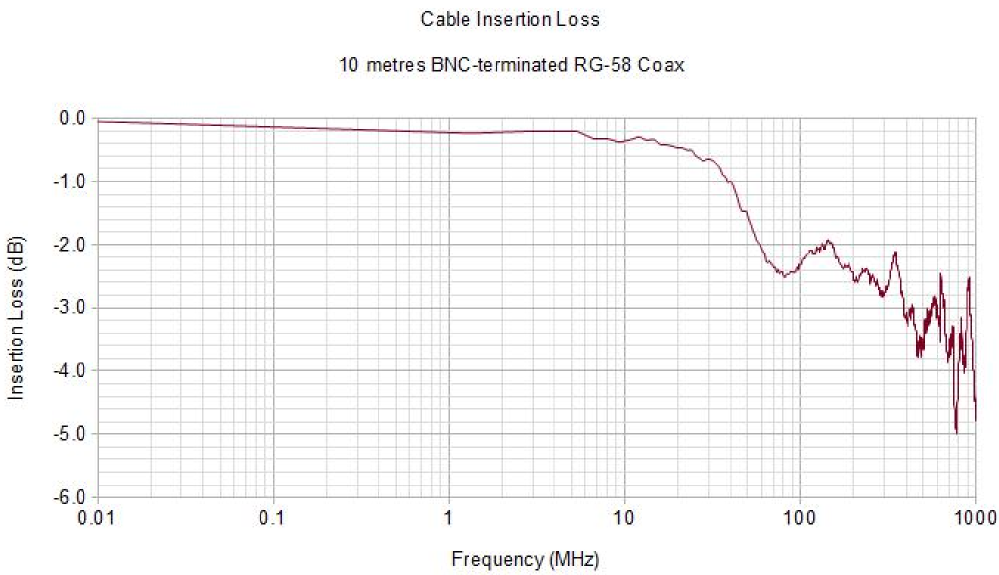

Figure 5.10: 10 m Test Cable insertion loss

This cable insertion loss must be taken into consideration when undertaking EMI measurements beyond 30 MHz, otherwise the measurements could be up to 5 dB lower than the actual signal.

5.2.5 Selection of Spectrum Analysers

It was intended that very low-cost SDR dongles paired with public domain spectrum analysis software would be considered for viability. However, the bulk of these devices and the spectrum analysis software on offer in the public domain was neither stable, nor did they offer the key controls and many other operational criteria. Due to time constraints, this idea was dropped, but could be reconsidered in the future, if these systems were further developed.

After cost, the most challenging task in the selection of a Spectrum Analyser in finding one that will work down as low as 10 Hz. Most Spectrum Analysers are sold for RF work and usually do not scan lower than 9 kHz. There are speciality Audio Analysers that scan between 10 Hz and 100 kHz and extremely wide band Network Analysers or EMI Receivers that will scan a low as 10 Hz up to 20 GHz or even higher, but have a price-tag roughly between twenty and hundred thousand dollars.

Two models were accessible for purposes of this project:

- The American made Signal Hound SA44B, 1 Hz to 4.4 GHz, USB-based, software defined spectrum analyser and accompanying tracking generator TG44A, also USB-based. Both require a relatively capable PC to operate their bespoke software package "Spike". These units are shown in Figure 5.11.
- The Chinese made SIGLENT SSA3021X, 9 kHz to 2.1 GHz, standalone spectrum analyser. This instrument is shown in Figure 5.12.

Both of these spectrum analysers offer the basic controls and features that meet the basic criteria of a suitable spectrum analyser or measurement receiver to undertake sensor calibration and EMI pre-compliance measurements Section 3.3.2. A combination of the two units will be required to cover the entire frequency range required for this project (10 Hz to 1 GHz).

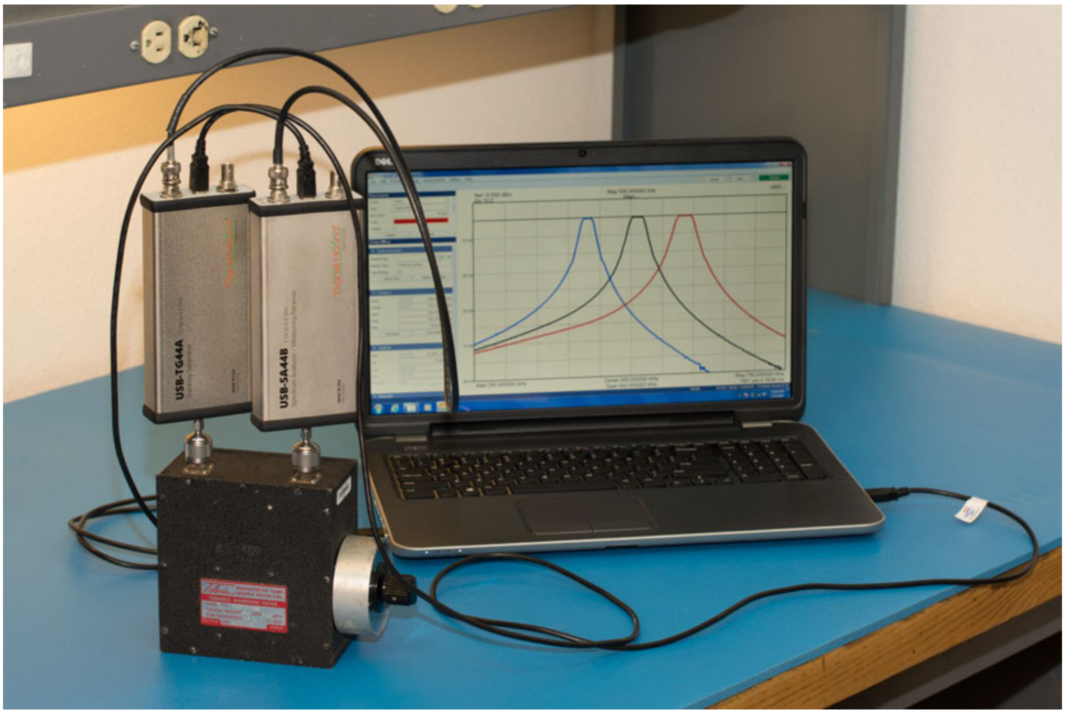

Figure 5.11: The Signal Hound SA44B spectrum analyser and TG44A tracking generator. Shown here in a configuration as a scalar network analyser, measuring the insertion loss of a tunable RF filter. The PC is running the bespoke Signal Hound "Spike" software.

Figure 5.12: Siglent SSA3021X spectrum analyser with in-built tracking generator.

5.3 CE101 Hardware Design, Verification and Simplified Test Design

As identified in Section 3.3.4, a cheaper, alternative current sensor is required. Cheap current sensors (more popularly named as current clamps) are in reasonably good supply due to the popular trend of household energy monitoring and other reasons driven by the popular photo-voltaic power generation trend. However, these devices are not specifically designed for EMI measurement and do not have accompanying calibration data.

5.3.1 Current Probe Hardware Design

The clamp selected is a YHDC SCT-015-0-15A-1V, shown in Figure 5.13. A full manufacturer's datasheet can be seen in Appendix C.

Figure 5.13: The YHDC SCT013-015 split-core current clamp

This clamp has a rated input (primary current) of 15 Arms and a rated frequency range of 50 Hz to 1 kHz. However, the required frequency range is nominally 30 Hz to 10 kHz. It was decided to verify the clamp's performance by undertaking the calibration procedure as discussed in Section 3.3.4. The model supplied had an unterminated cable end. A BNC was crimped onto it, with one end of the secondary winding shorted to the cable screen and BNC outer shell, with the other connected to the signal pin of the BNC.

5.3.2 Current Probe Calibration

The test configuration of the calibration setup was assembled in accordance with the illustration in Figure 3.6 and is shown in Figure 5.14. There was no need to include the optional amplifier as seen in Figure 3.6 in the test setup, as the Signal Generator provided a sufficiently high level for measurements to be successfully taken.

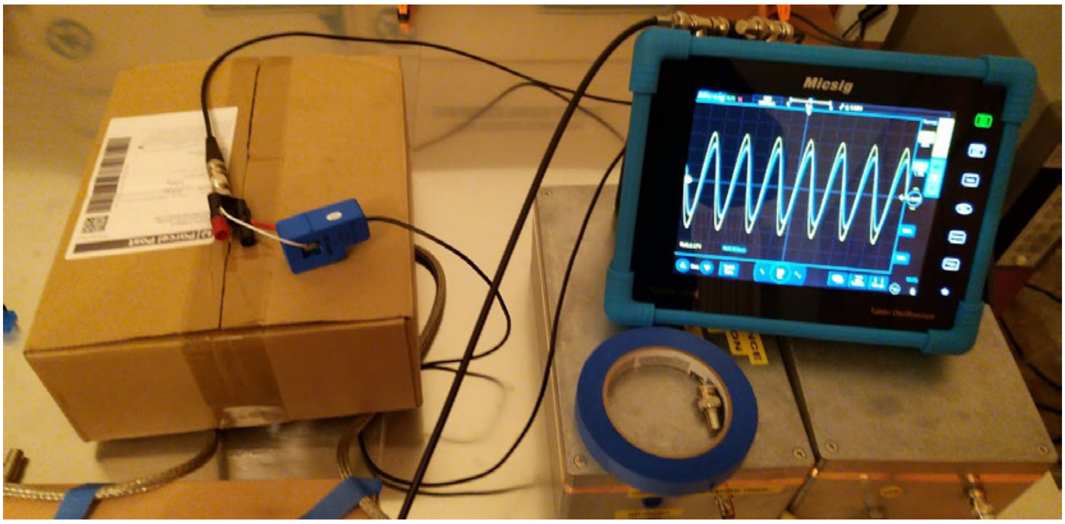

Figure 5.14: CE101 current sensor calibration setup.

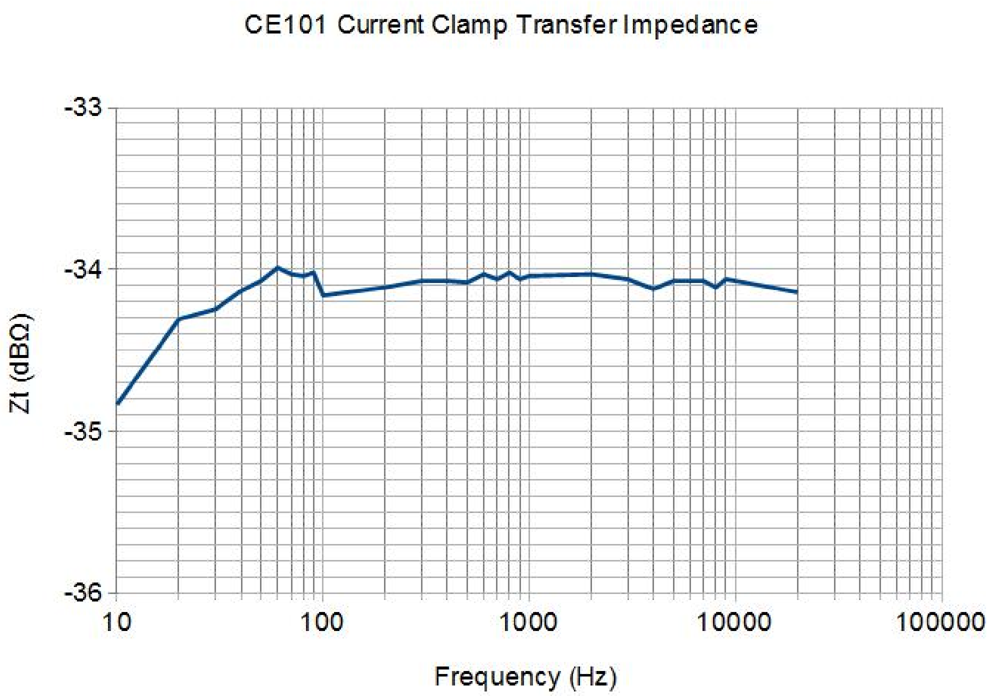

Figure 5.15: CE101 current sensor measured calibration curve

The resulting measurements, as seen in Figure 5.15, shows that the clamp is usable over the entire frequency range required for CE101 testing.

5.3.3 CE101 Test Hardware Verification

The following plots are based on the sensor verification test of CE101 in MIL-STD-461G. This procedure calls for the measurement of three specific test tones at 1.1 kHz, 3 kHz and 9.8 kHz, injected by a signal generator via the calibration setup illustrated in Figure 3.8. The Signal Hound spectrum analyser was used because of the low frequencies involved.

The HP3325B generator used was able to generate the levels identified without the aid of an amplifier. To simplify the configuration, the load resistor, R, as in Figure 3.8, was set at 50 Ω. Driving such a load allowed precise setting of the generator output in dBm. As discussed in Section 3.3.3, and arithmetic conversion is easily applied to convert from the required signal amplitude in dBμA to a readily selectable level in dBm, as listed in Table 3.1.

For the 1.1 kHz tone, an injected signal level of 85 dBμA was generated by applying a 12 dBm signal into the load resistor.

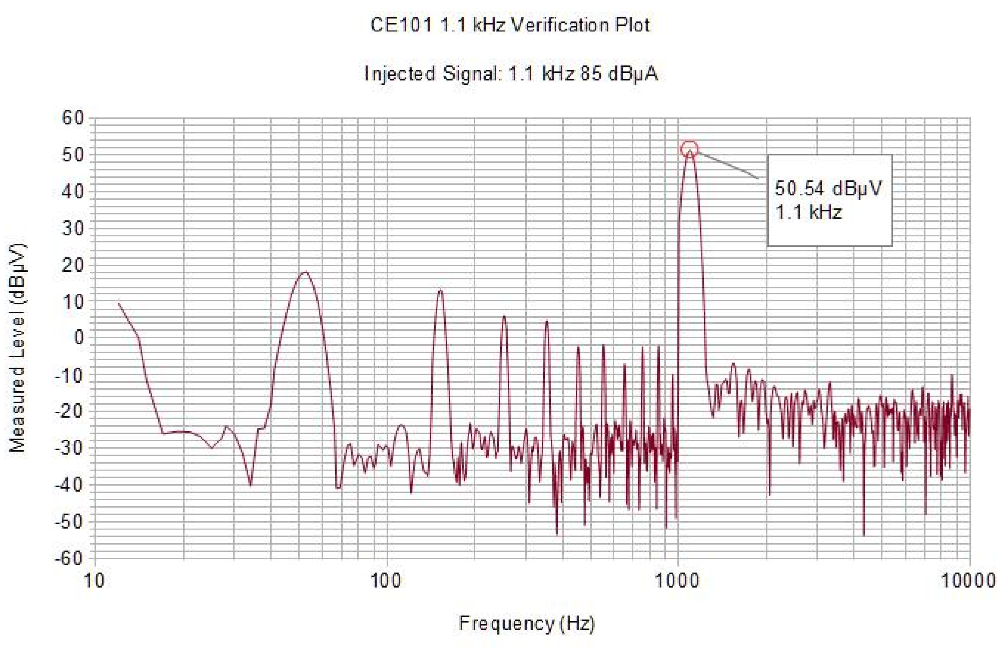

Figure 5.16: 1.1 kHz verification plot

As seen in Figure 5.16, a tone of level 50.54 dBμV was measured by the spectrum analyser. Applying the calibration offset from Figure 5.15 for 1.1 kHz and disregarding the very small cable loss at that frequency, the following expression is written, applying Equation 3.14:

50.54 dBμV + (-)(-34.1 dBΩ) = 84.6 dBμA, which is well within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

For the 3 kHz test tone, an injected signal level of 80 dBμA was selected, which required the generator to be set to 7 dBm.

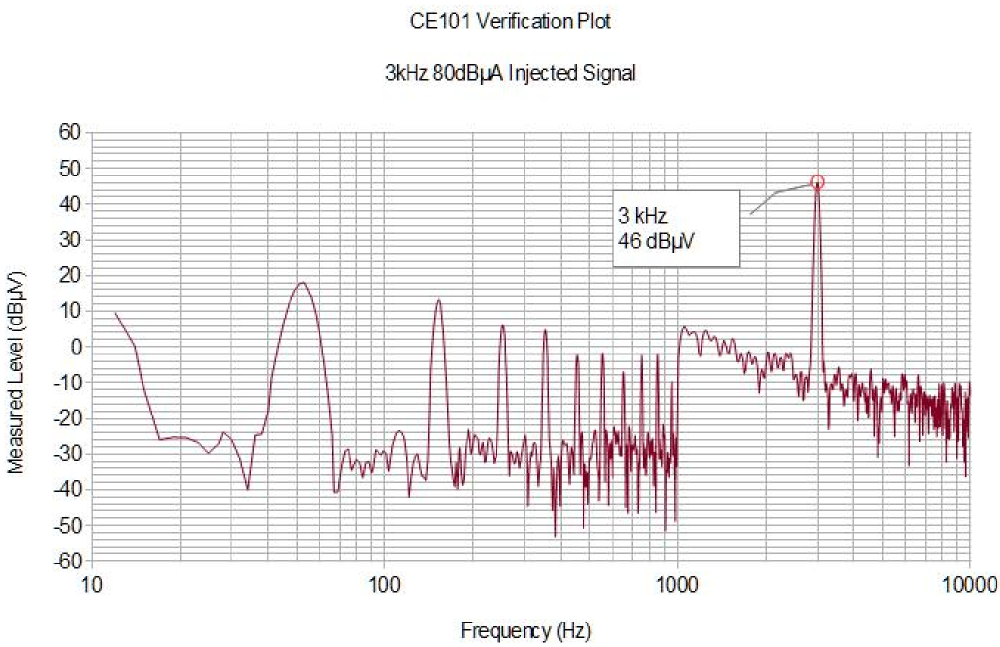

Figure 5.17: 3 kHz verification plot

As can be seen in Figure 5.17, a tone level of 46 dBμV was measured by the spectrum analyser. Applying the appropriate calibration offset from Figure 5.15 for 3 kHz and disregarding the very small cable loss at that frequency, the following expression is written, applying Equation 3.14:

46 dBμV + (-)(-34.1 dBΩ) = 80.1 dBμA, which is well within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

For the 9.8 kHz test tone, an injected signal level of 70 dBμA was selected, which required the generator to be set to -3 dBm.

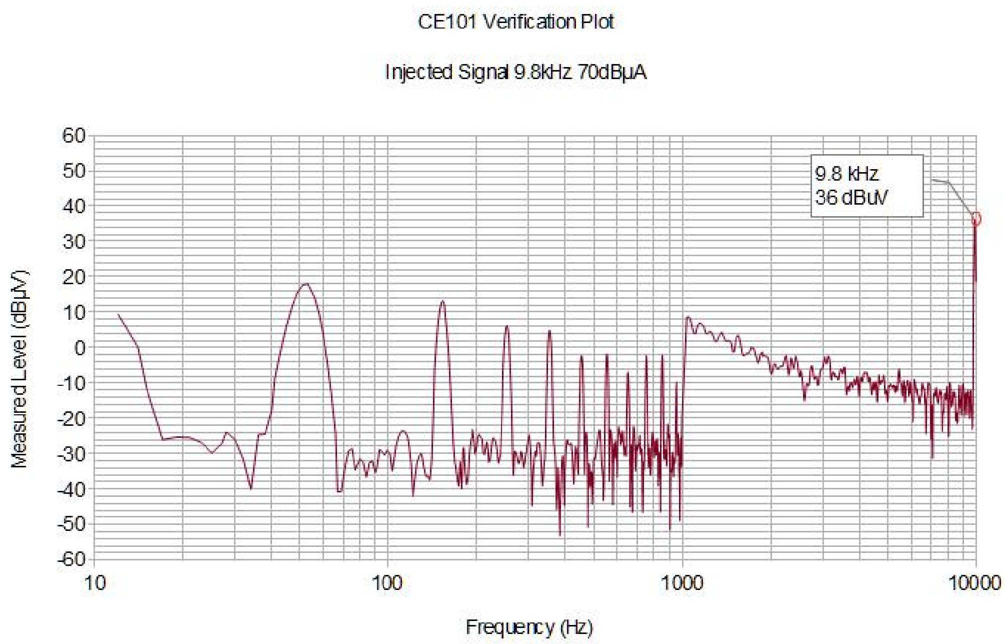

Figure 5.18: 9.8 kHz verification plot

As can be seen in Figure 5.18, a tone level of 36 dBμV was measured by the spectrum analyser. Applying the appropriate calibration offset from Figure 5.15 for 9.8 kHz and disregarding the very small cable loss at that frequency, the following expression is written, applying Equation 3.14:

36 dBμV + (-)(-34.1 dBΩ) = 70.1 dBμA, which is well within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

Therefore, the function and the calibration of the current clamp was verified to well within the required tolerance of $\pm$3 dB.

5.3.4 CE101 Simplified Test Protocol Design

The following is a simplified procedure for the CE101 test scanning and collection of spectrum analyser measurement data for later plotting and analysis.

The entire band of interest for CE101 is 10 Hz to 10 kHz, which covers two RBW settings as shown in Table 5.2.

Frequency Range	RBW Setting
10 Hz - 1 kHz	10 Hz
1 kHz - 10 kHz	100 Hz

Table 5.2: CE101 RBW settings

Hence, each complete CE101 scan will be made up of two smaller scans of the frequency ranges with respective RBW settings as shown in Table 5.2. The output data of these two scans are then concatenated so a single plot can be produced of the entire CE101 frequency range.

The following test protocol is based on the high level structure detailed in Section 3.3.9, and was specifically tailored for the conditions and equipment available.

The spectrum analyser settings required will include:

- Start and Stop Frequencies should be set as per Table 5.2.
- Select the appropriate RBW for the Frequency Range as per Table 5.2.
- The VBW should either be disabled or set to its maximum frequency.
- The spectrum analyser's input attenuator should be set to AUTO.
- the spectrum analyser's pre-amplifier should be set to ON.
- Select the amplitude units to "dBμV".
- Select an appropriate amplitude scale and reference level to frame the signal measured
- Connect a USB memory stick if required to capture data files

The CE101 Test Setup of Figure 2.19 should be assembled. Figure 5.19 shows the general layout of the test configuration. The power lines to the inputs of the LISNs should not be connected until all grounds are verified as connected.

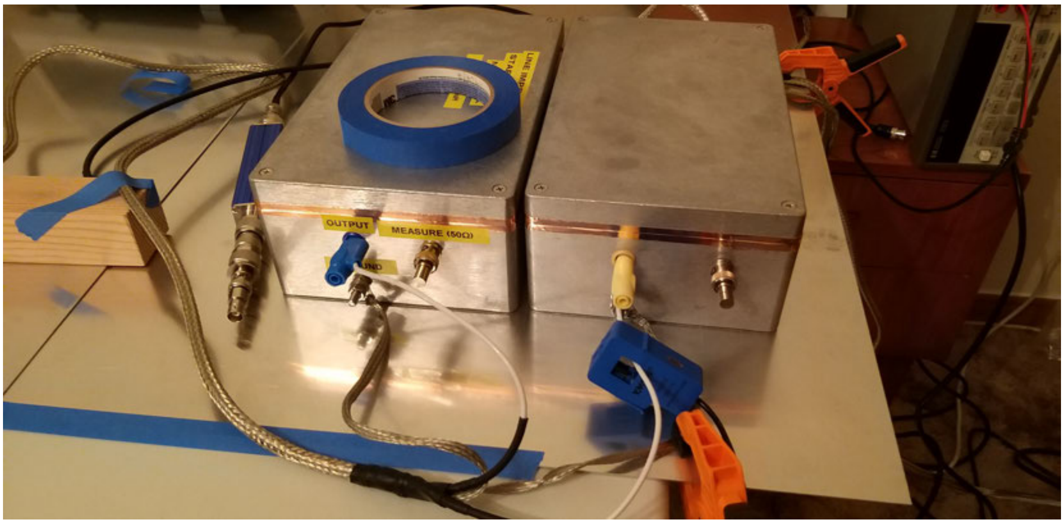

Figure 5.19: CE101 Test Setup with the current probe clamped around the output power line connected to LISN No. 2. Note that both LISNs have terminators connected to their measurement ports.

1. Verify that the test table ground plane is connected to ground.
2. Verify that the supply end of the power input leads are disconnected from the supply.
3. Connect only the screen of the input power leads to the ground stud on the LISNs' input side.
4. Connect only the screen of the output power leads to the ground stud on the LISNs' output side.
5. Connect the output power leads to the LISNs' output jacks.
6. Verify that the power supply is setup to provide 115 VAC and then verify that it is switched off.
7. Connect the input power leads to the input jacks of the LISNs.
8. Connect the output power leads to the EUT power input socket.
9. Connect the measurement lead from the spectrum analyser to the current probe (clamp).
10. Verify that both LISNs have 50 Ω terminators connected to their measurement ports.
11. Selecting a LISN, clamp the probe around the output power lead at approximately 5 cm from the LISN connection.

12. Use the spectrum analyser (using the max-hold feature) to take a scan of the ambient noise current present on the power lead and save the data (.CSV format preferred) with an appropriate name identifying the scan and the LISN or power line measured.

13. Turn on the AC mains supply

14. Turn on the EUT, if it is separately switched

15. Use the spectrum analyser (after clearing the max-hold feature) to take a scan of the conducted current present on the power lead and save the data (.CSV format preferred) with an appropriate name identifying the scan and the LISN or power line measured.

16. Turn off the EUT and the AC mains supply and repeat for the other LISN from Step 10.

The resulting .CSV files are then opened with a spreadsheet program such as OpenOffice Spreadsheet or Microsoft Excel. The data for the two frequency ranges should be concatenated and a X-Y Scatter Diagram chart should be created with a logarithmic Frequency axis (in Hz) and linear Measured Level (in dBμV) axis. Figure 5.16 shows a typical example of this kind of concatenated plot.

In comparison with the ambient readings, any peaks attributed to the EUT, should be adjusted to dBμA as was shown in the verification testing of Section 5.3.3. These levels should then be compared to the limits line of Figure 2.20. Any adjusted peaks found to be within 3 dB of the limit or above should be tabulated as emissions of concern.

5.4 CE102 Verification and Simplified Test Design

CE102 testing depends entirely on the operation and calibration of the LISNs, of which the hardware design was discussed in Section 5.2.3. Therefore, the calibration procedure outlined in Section 3.3.5 previously applied to the hand constructed LISNs is now used in conjunction with an allowance for the 20 dB attenuator connected to the LISN measurement port as per Figure 3.11.

5.4.1 CE102 Test Hardware Verification

The following is based on the verification test of CE102 in MIL-STD-461G. This procedure calls for the measurement of four specific test tones at 10.5 kHz, 100 kHz, 1.95 MHz, 9.8 MHz, injected by a signal generator via the calibration setup illustrated in Figure 3.11.

The Signal Hound spectrum analyser was selected purely as it was already set-up from previous CE101 verification. Either the Signal Hound or the SIGLENT could have been used for these measurements, since the lowest frequency required to be measured in CE102, starts at 10 kHz. The complete CE102 frequency range, is detailed in Table 5.3.

The CE102 verification test setup of Figure 3.11 should be assembled. Figure 5.20 shows the physical layout of this setup.

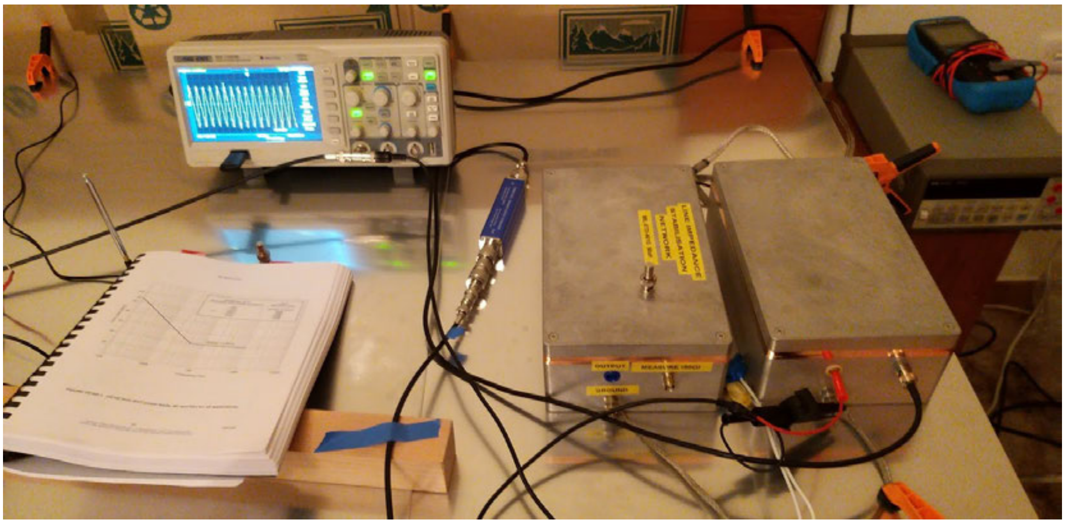

Figure 5.20: Physical layout of the CE102 verification setup. This configuration shows LISN No. 2 connected. The injected signal is being monitored using an oscilloscope, seen in the background.

It should be noted that the figures achieved for both LISNs were, for all practical purposes, identical. Therefore, the following results are only presented once and are intended to show verification of both LISNs. The signal generator used was the HP3325B, which can be set to output levels in dBm (into 50 Ω). The MIL-STD-461G CE102 "intergrity check" requires that the four tones be injected at least 6 dB below the required emissions limit for those frequencies as illustrated in Figure 2.22.

In the interests of clarity, only the frequency range pertaining to the specific test tone, as per Table 5.3 was measured and plotted

For the 10.5 kHz test tone, a signal level of 90 dBμV was injected into the LISNs' power output ports as a signal generator level of -17 dBm.

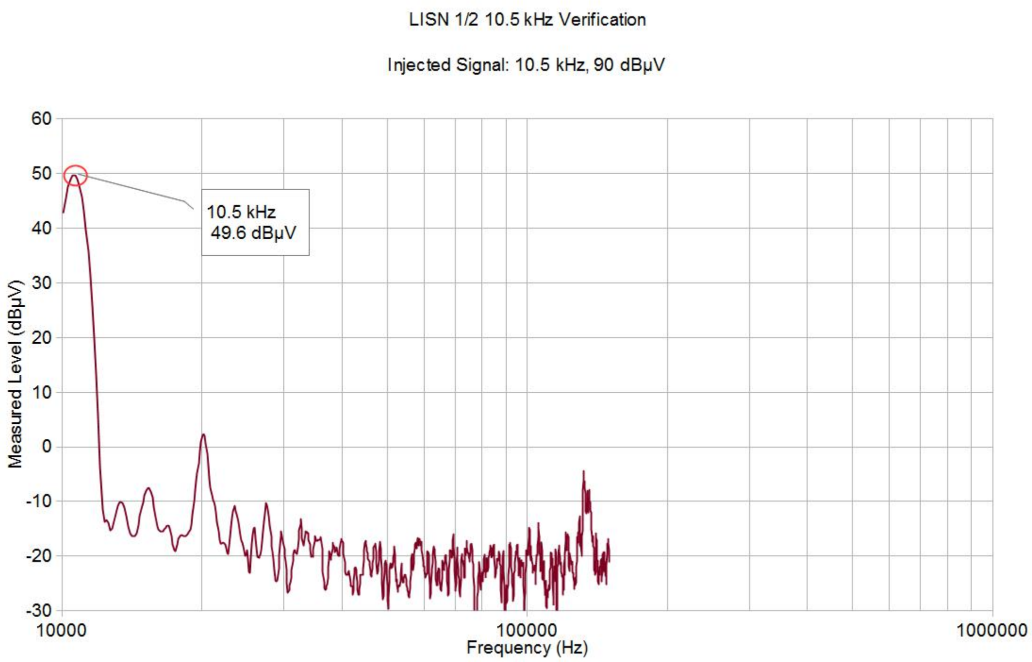

Figure 5.21: 10.5 kHz Verification plot

As can be seen in Figure 5.21, a tone level of 49.6 dBμV was measured by the spectrum analyser. Adding a 20 dB allowance for the attenuator and applying the appropriate calibration offset from the LISNs' insertion loss of Figure 5.8 for 10.5 kHz and disregarding the very small cable loss at that frequency, the following expression is written, applying Equation 3.15:

49.6 dBμV + 20 dB + (-)-17 dBΩ) = 88.6 dBμV, which is well within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

For the 100 kHz test tone, a signal level of 72 dBμV was injected into the LISNs' power output ports as a signal generator level of -35 dBm.

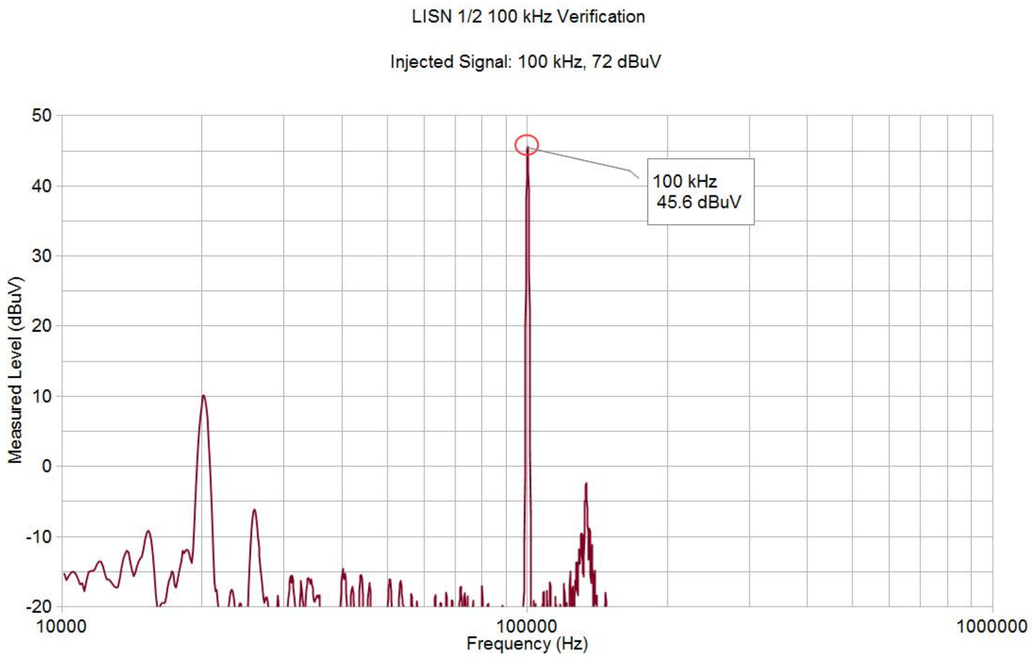

Figure 5.22: 100 kHz Verification plot

As can be seen in Figure 5.22, a tone level of 47.5 dBμV was measured by the spectrum analyser. Adding a 20 dB allowance for the attenuator and applying the appropriate calibration offset from the LISNs' insertion loss of Figure 5.8 for 100 kHz and disregarding the very small cable loss at that frequency, the following expression is written, applying Equation 3.15:

45.6 dBμV + 20 dB + (-)-4.5 dBΩ) = 69.6 dBμV, which is within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

For the 1.95 MHz test tone, a signal level of 55 dBμV was injected into the LISNs' power output ports as a signal generator level of -52 dBm.

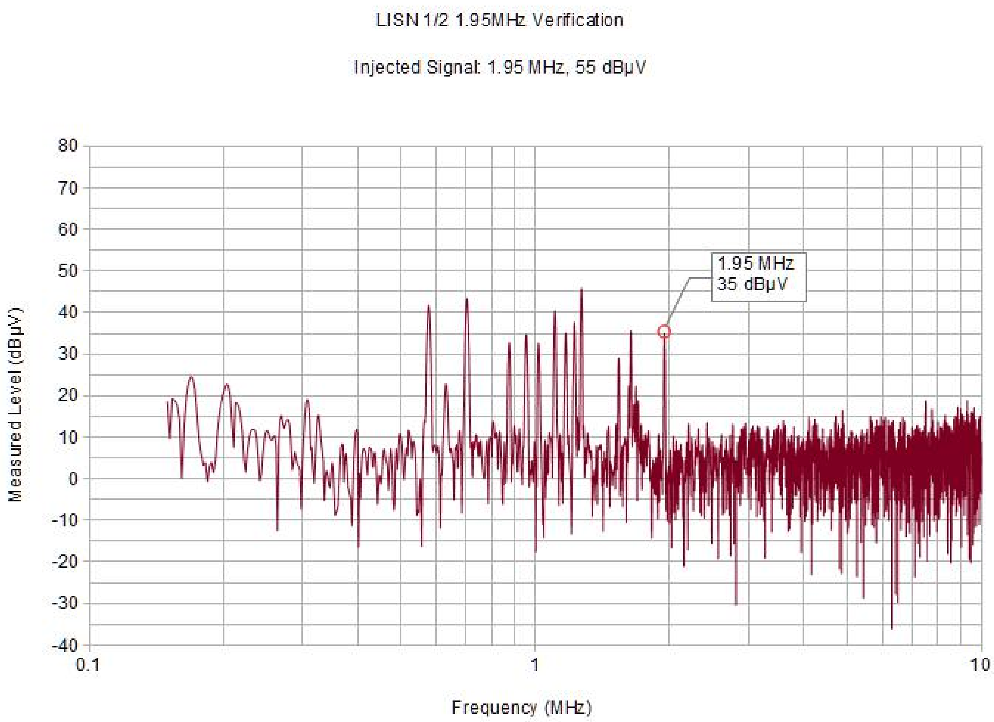

Figure 5.23: 1.95 MHz Verification plot

As can be seen in Figure 5.23, a tone level of 35 dBμV was measured by the spectrum analyser. Adding a 20 dB allowance for the attenuator and disregarding the tiny calibration offset from the LISNs' insertion loss of Figure 5.8 for 1.95 MHz and the very small cable loss at that frequency, the following expression is written:

35 dBμV + 20 dB = 55 dBμV, which is exactly correct.

For the 9.8 MHz test tone, a signal level of 55 dBμV was injected into the LISNs' power output ports as a signal generator level of -52 dBm.

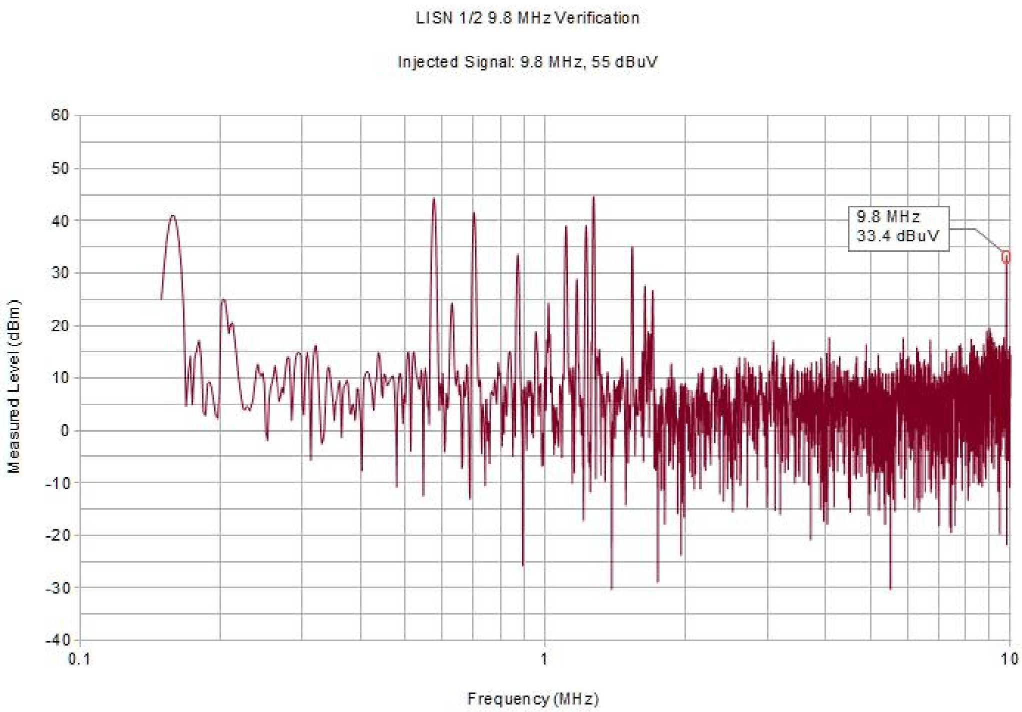

Figure 5.24: 9.8 MHz Verification plot

As can be seen in Figure 5.24, a tone level of 33.4 dBμV was measured by the spectrum analyser. Adding a 20 dB allowance for the attenuator and disregarding the tiny calibration offset from the LISNs' insertion loss of Figure 5.8 for 9.8 MHz and the very small cable loss at that frequency, the following expression is written:

33.4 dBμV + 20 dB = 53.4 dBμV, which is well within the $\pm$3 dB tolerance accepted by MIL-STD-461G.

Therefore, the function and the calibration of the LISNs was verified to well within the required tolerance of $\pm$3 dB.

5.4.2 CE102 Simplified Test Protocol Design

The following is a simplified procedure for the CE102 test scanning and collection of spectrum analyser measurement data for later plotting and analysis.

The entire band of interest for CE102 is 10 kHz to 10 MHz, which covers two RBW settings as shown in Table 5.2.

Frequency Range	RBW Setting
10 kHz - 150 kHz	1 kHz
150 kHz - 10 MHz	10 kHz

Table 5.3: CE102 RBW settings

Hence, each complete CE102 scan will be made up of two smaller scans of the frequency ranges with respective RBW settings as shown in Table 5.3. The output data of these two scans are then concatenated so a single plot can be produced of the entire CE102 frequency range.

The following test protocol is based on the high level structure detailed in Section 3.3.9, and was specifically tailored for the conditions and equipment available.

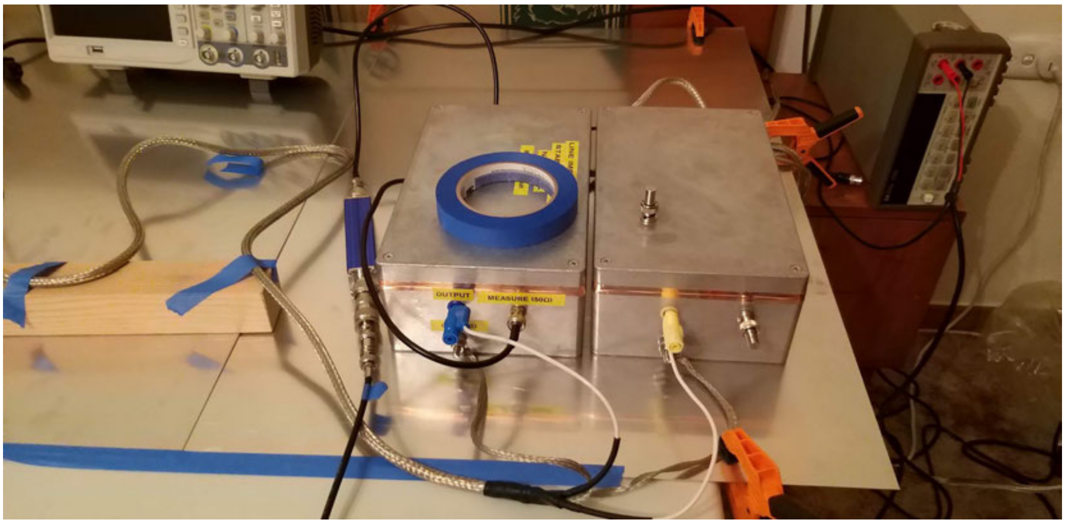

Figure 5.25: CE102 configuration connected to the measurement port of LISN No.1

The spectrum analyser settings required will include:

- Start and Stop Frequencies should be set as per Table 5.3.
- Select the appropriate RBW for the Frequency Range as per Table 5.3.
- The VBW should either be disabled or set to its maximum frequency.
- The spectrum analyser's input attenuator should be set to AUTO.

- the spectrum analyser's pre-amplifier should be set to ON.
- Select the amplitude units to "dBμV".
- Select an appropriate amplitude scale and reference level to frame the signal measured
- Connect a USB memory stick if required to capture data files

The CE102 Test Setup of Figure 2.19 should be assembled. Figure 5.25 shows the general layout of the test configuration. The power lines to the inputs of the LISNs should not be connected until all grounds are verified as connected.

The following procedure should be undertaken for each frequency range in Table 5.3.

1. Verify that the test table ground plane is connected to ground.
2. Verify that the supply end of the power input leads are disconnected from the supply.
3. Connect only the screen of the input power leads to the ground stud on the LISNs' input side.
4. Connect only the screen of the output power leads to the ground stud on the LISNs' output side.
5. Connect the output power leads to the LISNs' output jacks.
6. Verify that the power supply is setup to provide 115 VAC and then verify that it is switched off.
7. Connect the input power leads to the input jacks of the LISNs.
8. Connect the output power leads to the EUT power input socket.
9. Connect the measurement lead from the spectrum analyser to the measurement port of the selected LISN with a 20 dB attenuator in circuit.
10. Verify that the other LISN has a 50 Ω terminator connected to its measurement port.
11. Use the spectrum analyser (using the max-hold feature) to take a scan of the ambient noise voltage present on the power lead and save the data (.CSV format preferred) with an appropriate name identifying the scan and the LISN or power line measured.

12. Turn on the AC mains supply

13. Turn on the EUT, if it is separately switched

14. Use the spectrum analyser (after clearing the max-hold feature) to take a scan of the conducted voltage present on the power lead and save the data (.CSV format preferred) with an appropriate name identifying the scan and the LISN or power line measured.

15. Turn off the EUT and the AC mains supply and repeat for the other LISN from Step 9.

The resulting .CSV files are then opened with a spreadsheet program such as OpenOffice Spreadsheet or Microsoft Excel. The data for the two frequency ranges should be concatenated and a X-Y Scatter Diagram chart should be created with a logarithmic Frequency axis (in Hz) and linear Measured Level (in dBμV) axis. Figure 5.16 shows a typical example of this kind of concatenated plot.

In comparison with the ambient readings, any peaks attributed to the EUT, should be adjusted to account for the 20 dB Attenuator and the insertion loss of the LISNs. These levels should then be compared to the limits line of Figure 2.22. Any adjusted peaks found to be within 3 dB of the limit or above should be tabulated as emissions of concern.

5.5 RE101 Hardware Design, Verification and Simplified Test Design

As identified in Section 3.3.6, a cheaper, alternative magnetic field sensor is required. As this is a very specialised loop antenna in terms of the specific design parameters as detailed in that section, it must be hand made, as off the shelf procurement is impractical.

5.5.1 Magnetic Field Sensor Hardware Design

The key parameters for the construction of RE101 compliant magnetic loop sensor are:

- The correct diameter of the coil windings,

- The correct type of winding wire, and
- An electrostatic shield

They key components required to construct this loop sensor are pictured in Figure 5.26.

The diameter of the coil windings is easily controlled by the use of a precise former on which to wind the coil. A precisely sized former was cut to a diameter of 13.3 cm with use of a small panel router rigged to cut a circle from a piece of scrap, laminated MDF.

The appropriate 7-strand, 41-AWG “Litz”-wire (individually insulated stands twisted together) was procured off the shelf. This wire was wound around the former thirty-six time, wrapped in paper tape and then stuffed into a precisely cut to length piece of split tubing to create a solid ring. This was again wrapped in paper tape to bind it together and give it more rigidity.

The electrostatic shield was constructed of non-ferro-magnetic copper tape, broken at the bottom of the loop to stop it from shorting the magnetic field, seen at the centre of Figure 5.26. This break in the shield also serves as the access way for the wires leading to the coil windings.

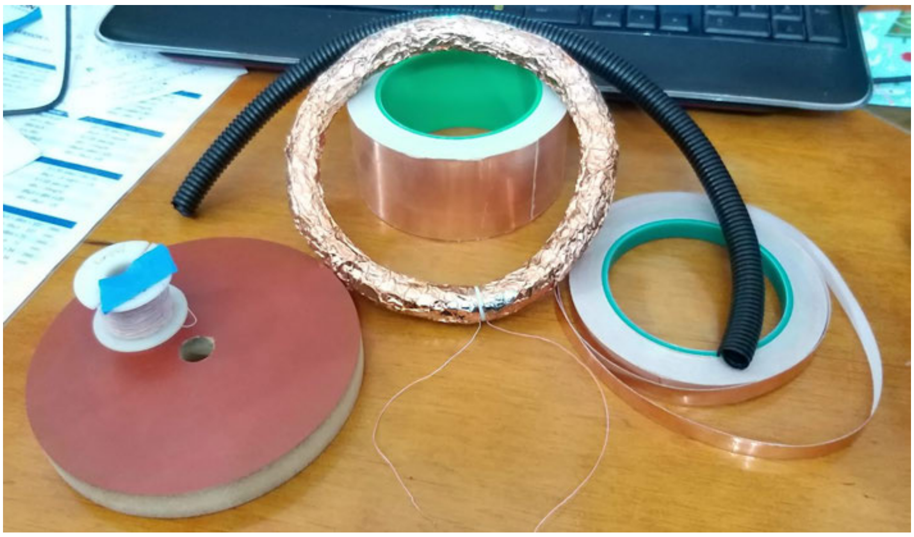

Figure 5.26: Hand making the RE101 magnetic loop sensor. From left to right, 13.3 cm former; a reel of 7 strand, 41 AWG, Litz wire; 10 mm plastic split-tubing; 50 mm copper tape; 10 mm copper tape; and in the centre, a completed sensor loop (note the split in the copper electrostatic shield, where the internal coil ends protrude).

As shown in Figure 5.27, the loop was then assembled in a small, non-conductive, drilled project box, where the shield and one leg of the coil was connected to the outer body shell (screen) of a female BNC panel connector. The other leg of the coil was connected to the signal pin of the connector. The internal assembly was coated in epoxy resin to provide rigidity, especially due to the very delicate Litz-wire leads.

The entire loop assembly was then precisely epoxied to a piece of MDF to provide a rigid stand for the loop as well as a pre-set spacer of 7 cm length to help situate the loop during testing.

Figure 5.27: Completed, hand-made RE101 magnetic loop sensor.

In accordance with the guidance of MIL-STD-461G, the DC resistance of the loop was measured as 9.9 Ω, which was under the allowable maximum of 10 Ω of the specification, as shown in Figure 5.28.

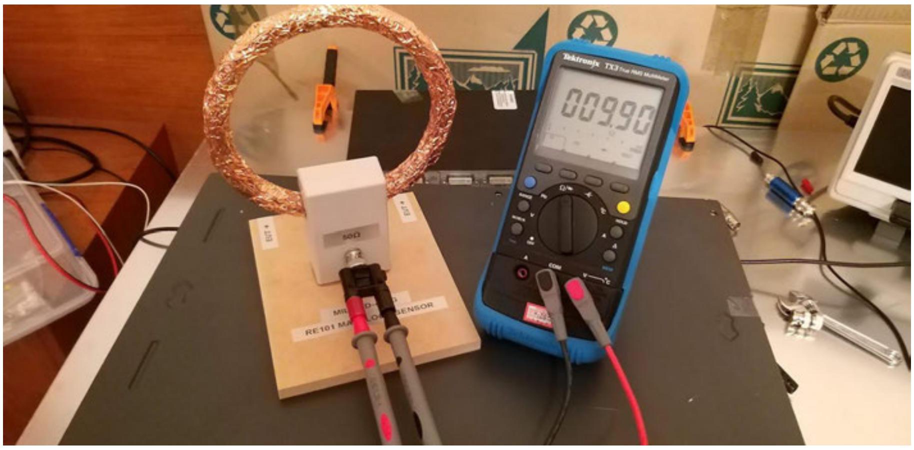

Figure 5.28: Loop sensor resistance test (required to be no more than 10 Ω)

The inductance was also measured at almost 460 μH, as seen in Figure 5.29.

Figure 5.29: Loop Sensor inductance measurement

5.5.2 Magnetic Field Sensor Calibration

As detailed in Section 3.3.6, an RS01 loop was constructed with the guidance of the original RS01 loop construction details of MIL-STD-461A, which is seen in Appendix B.

The test configuration of the calibration setup was assembled in accordance with the illustration in Figure 3.13 and is shown in Figure 5.30.

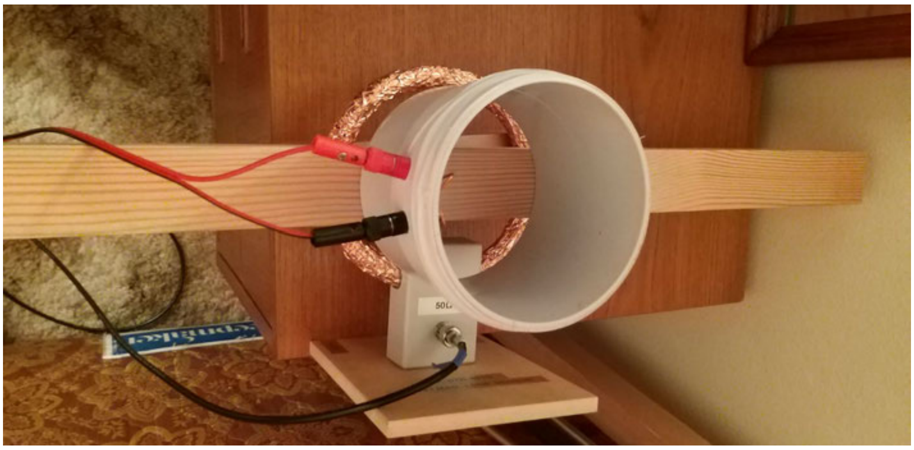

Figure 5.30: Using a hand-wound RS01 magnetic field coil to calibrate the RE101 magnetic loop sensor.

A HP3325B signal generator was used to provide the precise sinusoidal frequency signal to the input of the amplifier circuit in Figure 5.31. The amplifier was then used to drive a precise current through the RS01 coil and a 4 Ω, high-powered resistor. The voltage across the resistor was monitored with an oscilloscope to maintain the correct 1 Arms current as required for the calibration of the RE101 magnetic field sensor.

Figure 5.31: An off the shelf, single-channel amplifier circuit used to the drive the RS01 coil through a 4 Ω, high-powered resistor. Note that the DC power supply's exhaust fan was used to also cool the amplifier circuit, which was found to dissipate a lot of heat.

The calibration measurements were taken over the entire frequency range required for RE101 testing as detailed in Table 3.4.

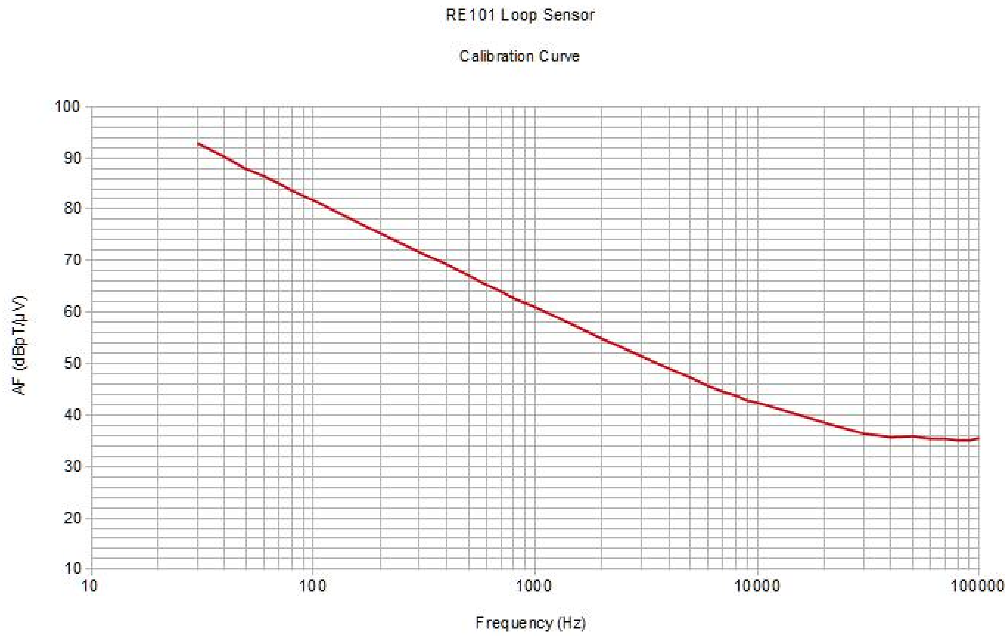

Figure 5.32: Magnetic sensor loop calibration curve

The Signal Hound spectrum analyser was used because of the low frequencies involved. As seen in Figure 5.32, the magnetic loop sensor is useable over the entire frequency range of Table 3.4.

5.5.3 RE101 Test Hardware Verification

In the case of the RE101 Magnetic Sensor Loop, the rather complicated manner of artificially generating a known magnetic field strength, as detailed in Section 5.5.2, makes the task of operational verification of this test sensor system impractical. The normal protocol for the verification of this loop, as recommended in MIL-STD-461G, is by inspection and measurement of its series resistance as shown in Figure 5.28.

This non-operational verification can be taken a little further by adding an inductance measurement with the aid of an LCR meter, as shown in Figure 5.29. This will verify that the previously established inductance of the loop has not changed significantly.

If both resistance and inductance measurements show correct figures, then it is very unlikely that the loop will not perform, as expected, in accordance with its calibration curve.

5.5.4 RE101 Simplified Test Protocol Design

The following is a simplified procedure for the RE101 test scanning and collection of spectrum analyser measurement data for later plotting and analysis.

The entire band of interest for RE101 is 30 Hz to 100 kHz, which covers three RBW settings as shown in Table 5.4.

Frequency Range	RBW Setting
30 Hz - 1 kHz	10 Hz
1 kHz - 10 kHz	100 Hz
10 kHz - 100 kHz	1 kHz

Table 5.4: RE101 RBW settings

Hence, each complete RE101 scan will be made up of three smaller scans of the frequency ranges with respective RBW settings as shown in Table 5.4. The output data of these three scans are then concatenated so a single plot can be produced of the entire RE101 frequency range.

The following test protocol is based on the high level structure detailed in Section 3.3.9, and was specifically tailored for the conditions and equipment available.

The spectrum analyser settings required will include:

- Start and Stop Frequencies should be set as per Table 5.4.
- Select the appropriate RBW for the Frequency Range as per Table 5.4.
- The VBW should either be disabled or set to its maximum frequency.
- The spectrum analyser's input attenuator should be set to AUTO.
- the spectrum analyser's pre-amplifier should be set to ON.
- Select the amplitude units to "dBμV".
- Select an appropriate amplitude scale and reference level to frame the signal measured

- Connect a USB memory stick if required to capture data files

The RE101 Test Setup of Figure 2.23 should be assembled. Figure 5.33 shows the detailed sensor placement, at 7 cm between the centreline of the loop to the face of the EUT. The general layout of this test configuration is as per CE102, except that both LISNs' measurement ports are terminated in 50 Ω. The power lines to the inputs of the LISNs should not be connected until all grounds are verified as connected.

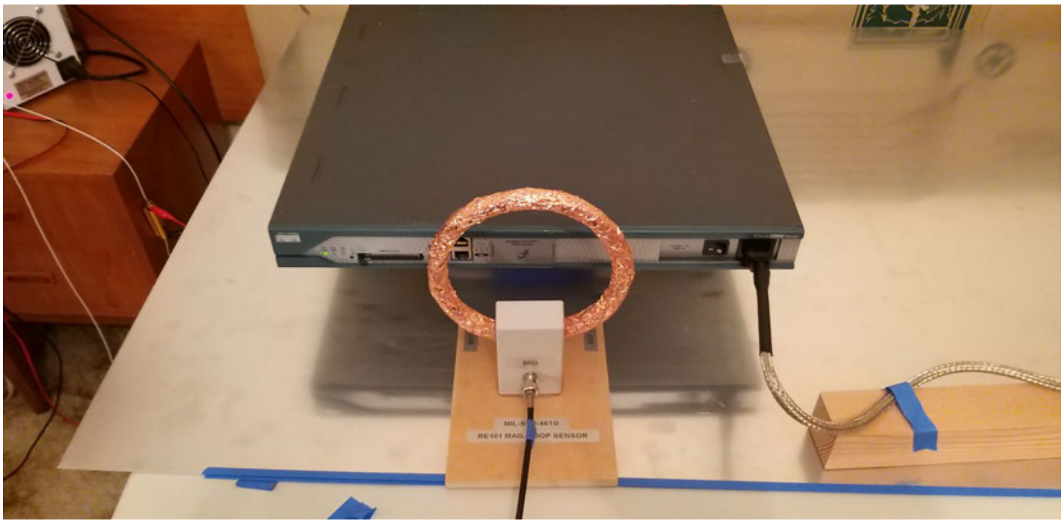

Figure 5.33: RE101 Test setup sensor detail - the rest of the setup is as per CE102, with both LISNs' measurement ports terminated in 50 Ω.

1. Verify that the test table ground plane is connected to ground.
2. Verify that the supply end of the power input leads are disconnected from the supply.
3. Connect only the screen of the input power leads to the ground stud on the LISNs' input side.
4. Connect only the screen of the output power leads to the ground stud on the LISNs' output side.
5. Connect the output power leads to the LISNs' output jacks.
6. Verify that the power supply is setup to provide 115 VAC and then verify that it is switched off.
7. Connect the input power leads to the input jacks of the LISNs.

8. Connect the output power leads to the EUT power input socket.

9. Connect the measurement lead from the spectrum analyser to RE101 Magnetic Loop Sensor, placed anywhere around the EUT, 7 cm from its face.

10. Use the spectrum analyser to take a scan of the ambient magnetic field noise, while moving the Loop Sensor around all four sides of the EUT, to determine if there are any significant noise components of which to take note. If significant components are discovered, save the data (.CSV format preferred) with an appropriate name identifying the position of the loop.

11. Turn on the AC mains supply

12. Turn on the EUT, if it is separately switched

13. Use the spectrum analyser to take a scan of the magnetic field strength, while moving the Loop Sensor around all four sides of the EUT, maintaining the 7 cm gap, to determine if there are any significant magnetic field components of which to take note.

14. Identify the position giving the strongest reading on the Spectrum Analyser and save the data (.CSV format preferred) with an appropriate name identifying the position of the loop.

15. Turn off the EUT and the AC mains supply and repeat for the other frequency bands of Table 5.4 from Step 9.

The resulting .CSV files are then opened with a spreadsheet program such as OpenOffice Spreadsheet or Microsoft Excel. The data for the two frequency ranges should be concatenated and a X-Y Scatter Diagram chart should be created with a logarithmic Frequency axis (in Hz) and linear Measured Level (in dBμV) axis. Figure 5.16 shows a typical example of this kind of concatenated plot.

Any peaks attributed to the EUT, should be adjusted to dBpT using the calibration curve of Figure 5.32. These levels should then be compared to the limits line of Figure 2.24. Any adjusted peaks found to be within 3 dB of the limit or above should be tabulated as emissions of concern.

5.6 RE102 Hardware Design, Verification and Simplified Test Design

As detailed in the preamble of Section 3.3.7, RE102 is an electric field emissions requirement, which normally covers the band between 10 kHz and 18 GHz. As previously established, this project is limited to to upper frequency limit of 1 GHz.

In Section 3.3.7, it was determined that, in accordance with MIL-STD-461G, three separate electric field sensing antennas are required to cover this range.

- A 104 cm Rod Antenna,
- A Biconical Antenna, and
- A Log-Periodic Dipole Array (LPDA) Antenna.

The following details the design and calibration of each antenna, followed by a common section on antenna verification and finally a simplified RE102 test protocol.

5.6.1 The 104 cm Rod Antenna Design

The 104 cm Rod (or monopole) Antenna is based on the guidance of MIL-STD-461G, which specifies that it is constructed as a monopole antenna element of length 1.04 m, with its feed-point installed above a square sheet-metal counterpoise with a minimum side length of 0.60 m.

As with most antennas used in EMI testing, the base material for all metallic sections was selected as aluminium. Both the flat sheet section making up the counterpoise and the cylindrical rod or monopole material was readily available from the local hardware supplier.

The final components selected were 3 mm thick aluminium sheet, cut to 600 mm $\times$ 600 mm and aluminium tubing of a 10 mm diameter with a wall thickness of 1 mm. Figure 5.39 shows the finished antenna based on these main components.

To affect a feed-point to the rod portion of the antenna, it was decided to use a combination of a BNC feed-through, pictured in Figure 5.34, and a modified BNC to “Banana”-

post adapter such as the Pomona Model 3430 Binding Post To BNC Male adapter, pictured in Figure 5.35. There is a full datasheet for the Pomona adapter in Appendix C.

The tensioning knob and nut was removed and a threaded sleeve was pressed into the base of the antenna rod to adapt this device to the base end of the rod. The fitted adapter is shown in Figure 5.36. This effectively insulated the rod from the counterpoise and provided a detachable mount for the rod, which also provided the feed point above the counterpoise, as pictured in Figure 5.37.

Figure 5.34: Typical BNC panel feed-through adapters

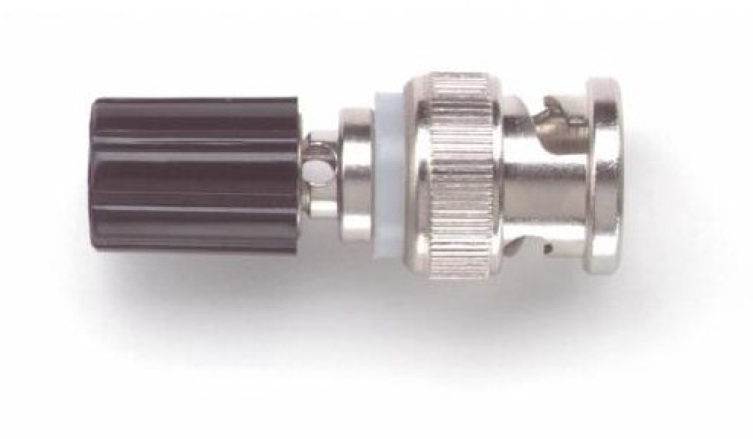

Figure 5.35: The Pomona 3439 BNC to Banana Post Adapter (www.pomonaelectronics.com). The tensioning knob and nut was removed and a threaded sleeve was used to adapt this device to the base end of the rod portion of the antenna.

Figure 5.36: BNC Adapter fitted to base of rod element.

The rod antenna is identified in MIL-STD-461G and its referenced standards as having a high impedance at its terminals and would, for professional purposes, normally have an active matching network to interface it to the typically 50 Ω measurement receiver. It was decided that an active matching network was impractical to research, design and build for this project, so a much simpler approach was required.

Figure 5.37: Finished mount of the rod antenna to the counterpoise, using the modified BNC binding post and the BNC feed-through.

The ThorLabs EF 500 DC-Block, pictured in Figure 5.38, offered both excellent bandwidth and the ability to match a high impedance with the required 50 Ω system of the test configuration. The DC-Block is connected directly to the BNC coupler under the counterpoise and acts as a passive impedance matching network. There is a full datasheet for the DC-Block in Appendix C.

Figure 5.38: The ThorLabs EF 500 DC-Block and matching network (thorlabs.com).

MIL-STD-461G gives clear guidance that the counterpoise in not to be directly coupled to the ground plane, but be indirectly coupled via a Coaxial cable screen, attenuated by a ferrite choke of a type providing approximately 20 Ω to 30 Ω at 20 MHz. This choke should be clamped over the outer screen of a coaxial cable between the rod feed point and the ground plane directly below the counterpoise, as pictured in Figure 2.26. The bond to the ground plane is managed through an L-bracket and another BNC feed-through coupling the antenna feed line to the measurement cable from the spectrum analyser.

Figure 5.39: Finished RE102, 1.04 cm Rod

The mounting arrangement of the whole antenna assembly is a simply constructed wooden base with rubber feet, which holds a square-section, wooden pole of the appropriate length for the given antenna. The height dimensions are detailed for the antenna centre in Figure 2.26. Two identical 104 cm Rod Antennas were built.

5.6.1.1 Rod Antenna Calibration

As detailed in Section 3.3.7.1, the 104 cm Rod Antenna is calibrated using the "Equivalent Capacitance Substitution Method" (ECSM), where the rod element is substituted for a capacitance, which is fed directly by a test signal. A 10 pF Siver-Mica capacitor is specified in MIL-STD-461G, SAE ARP958D and ANSI C63.5 standards for the calibration of this antenna. ANSI C63.5, Annex E provides construction details for a an assembly, called a "dummy load", to precisely hold and screen this capacitor to help control the consistency of test results (MIL-STD-461G 2015, SAE 2003, ANSI 2017). Figure 5.40 shows the internal structure of the dummy load.

Figure 5.40: ECSM dummy load assembly.

Figure 5.41: RE102 104 cm Rod Antenna calibration setup using the ECSM dummy load

As detailed in Section 3.3.7.1, the calibration setup illustrated in Figure 3.15 shows how the dummy load replaces the vertical rod element of the antenna assembly. Figure 5.41, shows the physical implementation of this setup.

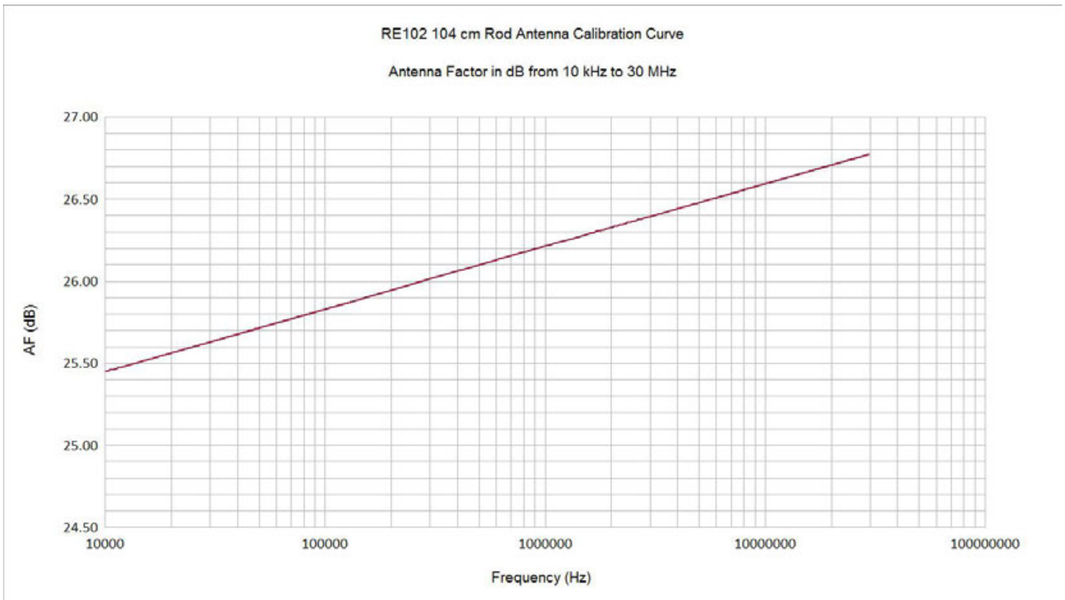

Figure 5.42: Calibration curve (Antenna Factor) for the 104 cm Rod Antenna

A HP3325B signal generator was used to provide the precise sinusoidal frequency signal to the input of the dummy load via a 10 dB attenuator, as in Figure 3.15. The calibration measurements were taken, with the Signal Hound spectrum analyser in dBμV over the entire frequency range required for the rod antenna frequency range, in accordance with the calibration intervals detailed in Table 3.5. These measurements for V_D and V_L were captured and processed in accordance with the calibration process of Section 3.3.7.1 to provide a calibration (Antenna Factor) curve as shown in Figure 5.42.

5.6.2 The Biconical Antenna Design

The design of the RE102 Biconical Antenna was based on the established design of MIL-STD-461A of August, 1968. The original construction details, which are duplicated in Appendix B, were used as a guide from a general dimensional as well as an electrical design standpoint. However, the original design required a considerable amount of precision machining, aluminium welding and electrical components no longer available for purchase.

Therefore, it was necessary to adapt modern componentry and readily available materials and lower cost processes to construct a similar biconical antenna, which closely approximated the original design from an electrical and RF perspective. Essentially, the antenna consisted of two symmetrically opposite conical cage assemblies, connected in the middle by a non-conductive block and mount assembly. Electrically, the antenna is a balanced device with no reference or ground. The original design calls out a specific BALUN to connect the antenna to the unbalanced measurement system. This BALUN is no longer commercially available.

Figure 5.43: The inner and outer end-caps. Seen here already machined and cleaned.

Upon review of the original design drawings, it was apparent that the inner and outer end-caps were critical to the structural integrity of the antenna assembly and key to maintaining its shape, which was considered critical to performance, especially at the 1 m measurement distance. It was decided that the end-caps would be machined of aluminium, as seen in Figure 5.43, and the centre-rod of each cage would provide the strength to hold the cage together and would be required to be made of thicker, more expensive material, as can be seen in Figure 5.44. The outer cage elements would be made of thinner, cheaper material. The centre block and mount would be made of timber. A more modern BALUN was selected and would be strapped to the mount arrangement and wired to the two cages, interfacing them to the unbalanced, coaxially interconnected measurement system.

Figure 5.44: Concical cages showing inner end-caps. Here they are hanging while the conductive glue, used to fix the thinner outer cage elements, is drying.

The material of the outer cage elements was selected as 3.2 mm diameter aluminium TIG welding filler rods. This material is very soft, but was in plentiful supply and easy to bend into shape. It was decided to use conductive glue to fix them into place. The centre-rod was selected to be higher-grade machining aluminium and was threaded at either end to be screwed into the end-caps. Figure 5.44, shows the inner end of the cage assembly with the centre-rod screwed in and the outer elements glued in place.

The BALUN selected was the Minicircuits FTB-1-1+, which is a 50 Ω 200 kHz to 500 MHz RF Transformer, giving the convenience of BNC connectivity at both ends. A full datasheet for this BALUN is available in Appendix C. It is shown connected to the finished conical cages and mounted (strapped-down) to the wooden mid-structure in Figure 5.45. A view of the completed biconical antenna is shown in Figure 5.46.

Figure 5.45: BALUN and internal wiring of the Biconical Antenna

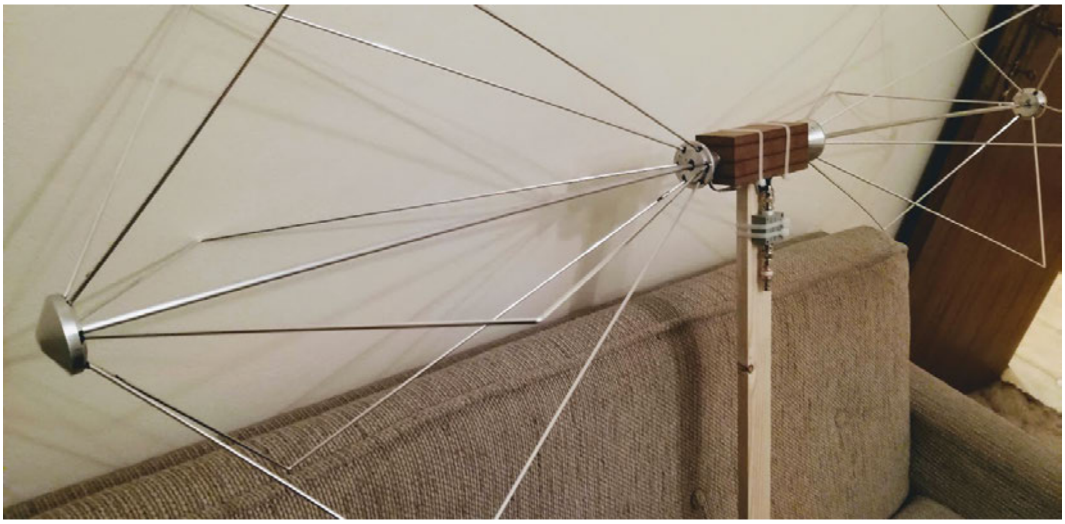

Figure 5.46: Completed Biconical Antenna

Two identical Biconical Antennas were built.

5.6.2.1 Biconical Antenna Calibration

The calibration method for the biconical antenna is based on the “Two identical antenna” method detailed in Section 3.3.7.2. This method requires that the two biconical antennas be arranged and connected in accordance with Figure 3.18. The measurement taken is essentially the insertion loss of the inter-antenna antenna system.

This is measured with the SIGLENT SSA3021X Spectrum analyser, configured as a scalar network analyser, utilising its tracking generator as a swept source with which to feed the transmitting antenna. 6 dB, wide-band attenuators were used in each of the transmit and receive cables. The insertion loss of the cables was already measured and presented in Figure 5.10.

Measurements were taken for both the horizontal and vertical polarisation. Figure 5.47 shows the physical layout of the biconical antenna calibration setup with horizontal polarisation. Figure 5.48 shows the layout for the vertical polarisation.

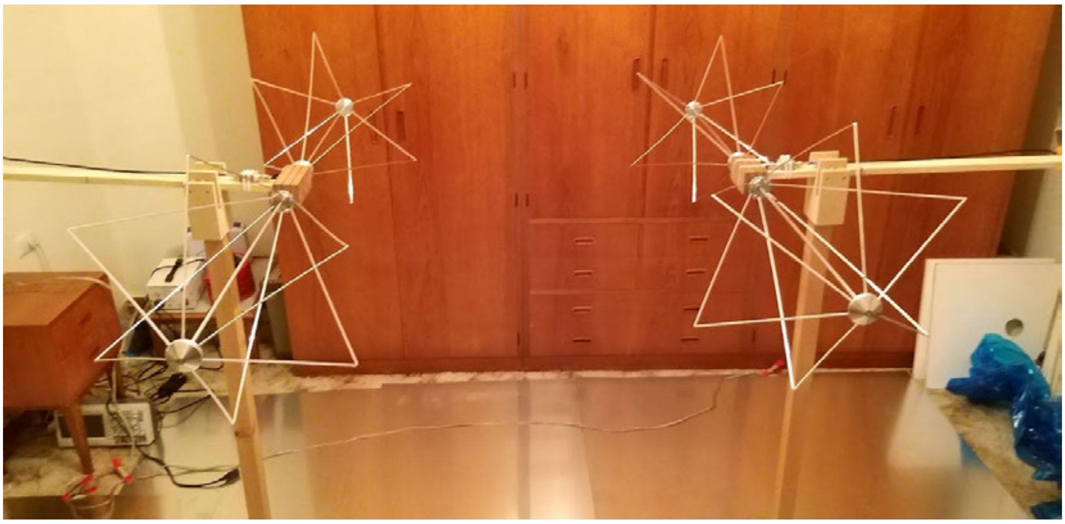

Figure 5.47: Biconical Antenna Calibration (Horizontal Polarisation).

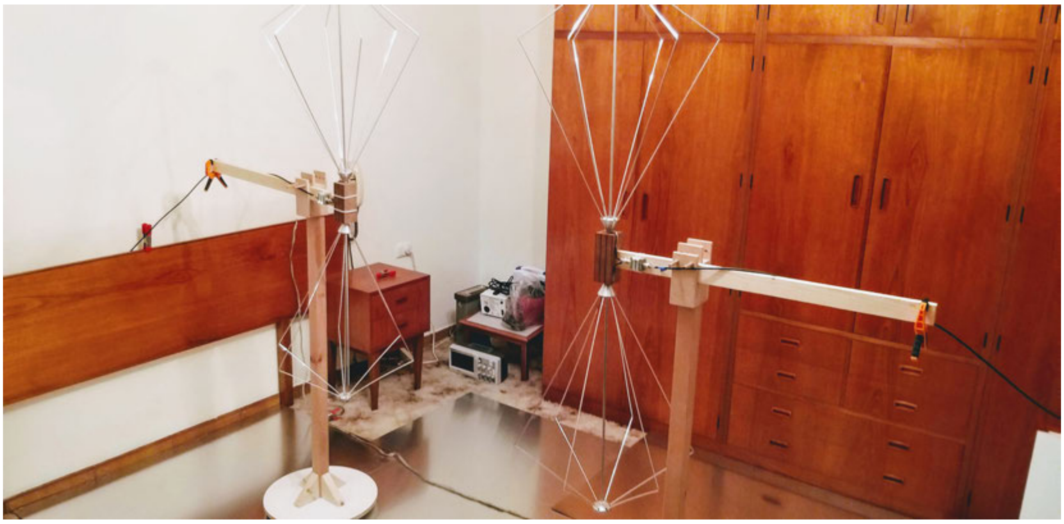

Figure 5.48: Biconical Antenna Calibration Vertical Polarisation).

The measurement data was processed as per the procedure of Section 3.3.7.2. Figure 5.49 shows the Antenna Factor calibration plot for the Biconical Antenna with Horizontal Polarisation and Figure 5.50 shows the Antenna Factor calibration plot for the Biconical Antenna with Vertical Polarisation.

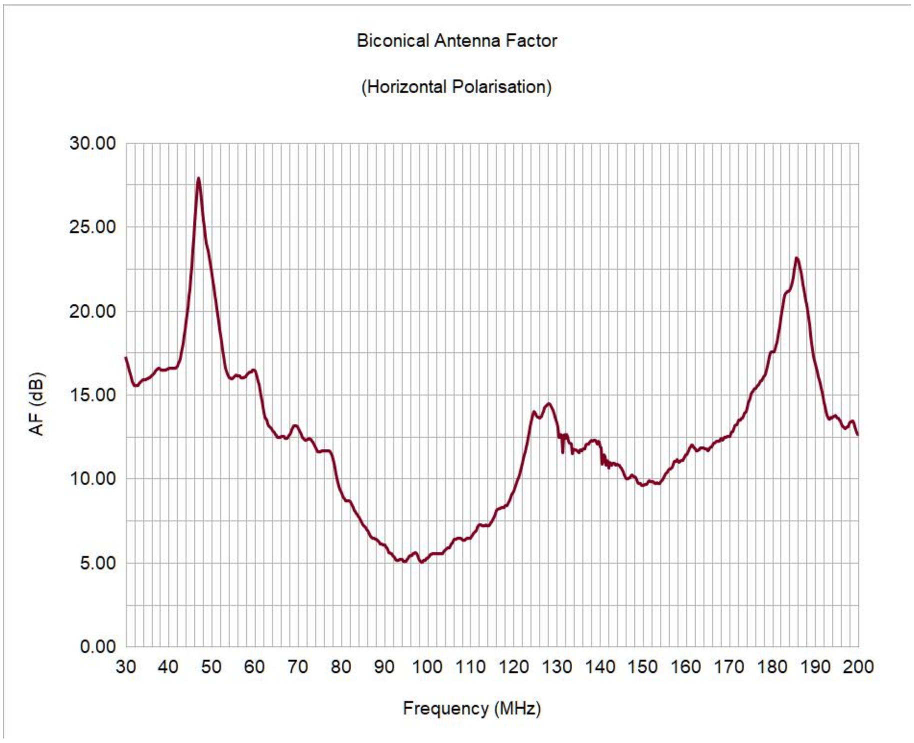

Figure 5.49: Calibration Curve (Antenna Factor) for the Biconical Antenna with Horizontal Polarisation

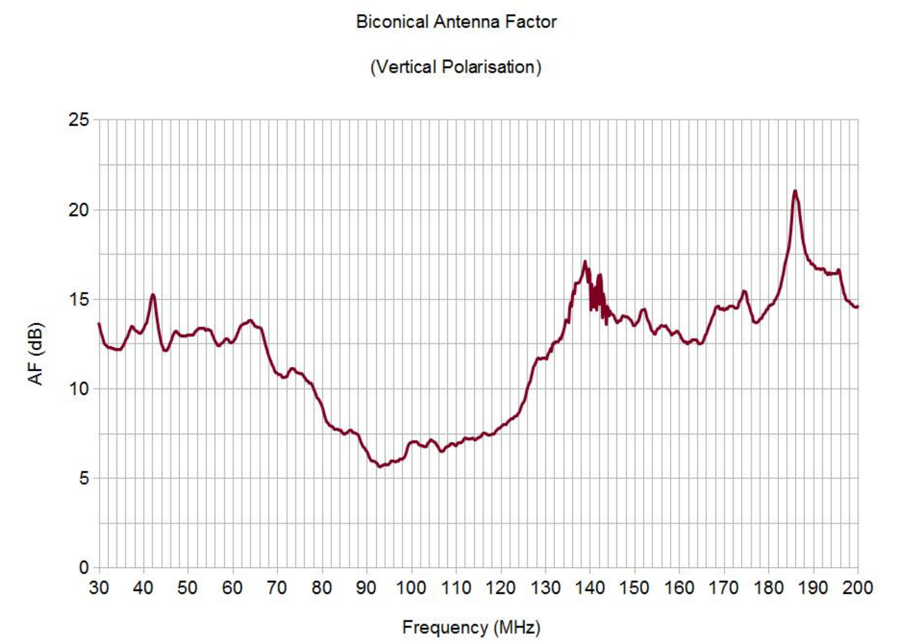

Figure 5.50: Calibration Curve (Antenna Factor) for the Biconical Antenna with Vertical Polarisation

5.6.3 The Log-Periodic Dipole Array (LPDA) Antenna Design

As mentioned in the preamble of this chapter, it was determined that a LPDA antenna would be used for measurement of the highest range of electric field strength emissions. This frequency range is from 200 MHz to 1 GHz, which roughly matches the modern, domestic television antenna. They are typically of an LPDA design, which covers the VHF and UHF television broadcast bands.

A very cheap version of this design was readily sourced from a very popular internet-based vendor. The LPDA sourced was a 32-element design, advertised to cover the television bands 174 MHz to 232 MHz and 470 MHz to 862 MHz, and was stated as being of 75 Ω impedance. Figure 5.51 shows a picture as advertised. This was an unbranded device, sold very cheaply, so while the specifications were stated, they should be verified. Two were procured for testing.

Figure 5.51: Picture of the LPDA as advertised (www.ebay.com.au).

The quality of the received antennas was obviously at the low end of the market. However, once the poor wiring was replaced with properly terminated RG-58 cable and a BNC female (as well, the pipe bracket removed as it shorted both booms), the antennas appeared to be sensitive to the ambient RF noise as measured on a 50 Ω spectrum analyser.

It was decided to verify the operation of these antennas by attempting calibration.

5.6.3.1 LPDA Antenna Calibration

The calibration method for the LPDA antenna is based on the "Two identical antenna" method detailed in Section 3.3.7.2. This method requires that the two LPDA antennas be arranged and connected in accordance with Figure 3.18. The measurement taken is essentially the insertion loss of the inter-antenna antenna system.

As with the Biconical Antenna, this is measured with the SIGLENT SSA3021X Spectrum analyser. The insertion loss of the cables was already measured and presented in Figure 5.10.

Measurements were taken for both the horizontal and vertical polarisation. Figure 5.52 shows the layout for the vertical polarisation.

Figure 5.52: Calibration setup for LPDA Antennas with Vertical Polarisation.

The measurement data was processed as per the procedure of Section 3.3.7.2. Figure 5.53 shows the Antenna Factor calibration plot for the LPDA Antenna with Horizontal Polarisation and Figure 5.54 shows the Antenna Factor calibration plot for the LPDA Antenna with Vertical Polarisation.

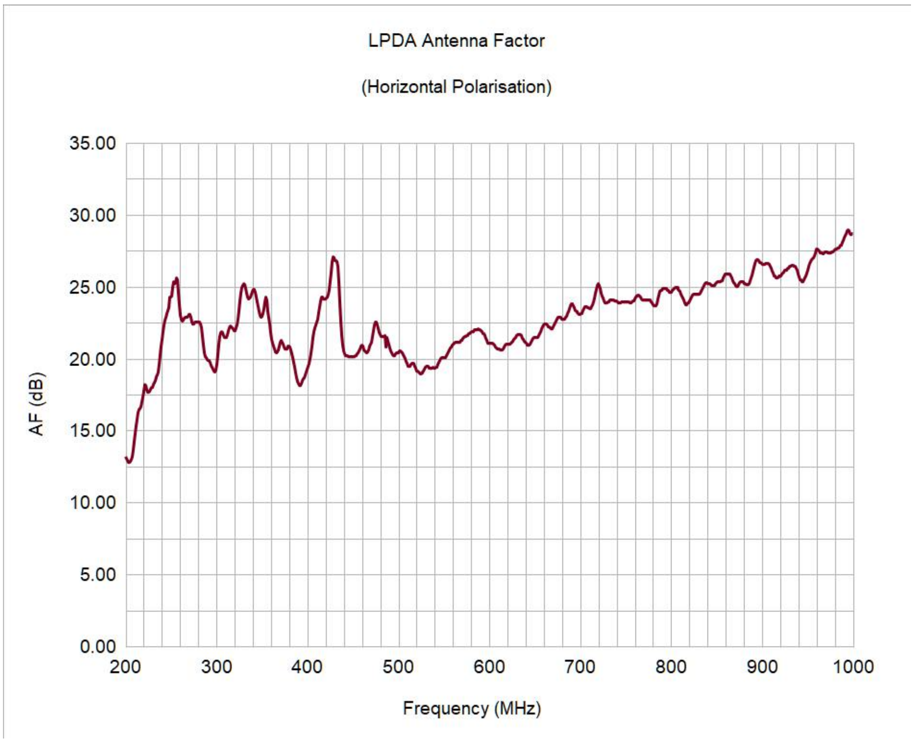

Figure 5.53: LPDA Calibration Curve (Antenna Factor) with Horizontal Polarisation.

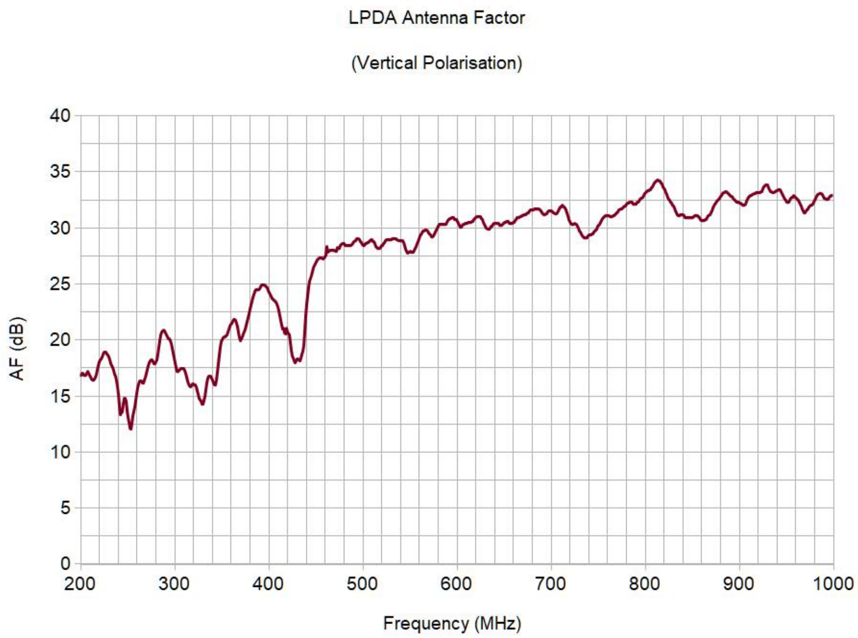

Figure 5.54: LPDA Calibration Curve (Antenna Factor) with Vertical Polarisation.

5.6.4 RE102 Antenna Verification

Ultimately, the best and most thorough verification test that could be made of the RE102 electric field strength measurement antennas would be to measure a known electric field strength or compare their performance with a calibrated field strength meter. However, neither of these options were available.

Therefore, assuming that the theory and mathematics of Section 3.3.7.2 and that, specifically the Equation 3.36 is correct. One could then assume that the most important variable to be verified is the antenna gain that was determined by the various experimental means, either by ECSM or the two antenna method. This data exists as part of the calculation of the various antenna factors and can be used to undertake spot verification tests using the method described in Section 3.3.8.

Using the two-antenna calibration setup illustrated in Figure 3.18, a known signal can be injected into the transmitting antenna circuit by an RF Signal Generator and measured via the receiving antenna on a spectrum analyser, the previously determined antenna gain figures could be independently verified by comparing experimental measurements with expected figures based on calculated values. The expected value can be determined by rearranging Equation 3.23 as follows.

$$P_{out} = P_{in} + 2G - 2CL - 147.6 + 20LOG\,(f) \tag{5.3}$$

Where:

P_{out} is the power driven out of the tracking generator's 50 Ω output in dBm,
P_{in} is the power measured at the spectrum analyser's 50 Ω output in dBm,
$2G$ is the combined gain of the two antennas in dB, and
$2CL$ is the cable loss in dB, including the 6 dB Attenuator
(both sides included).

Antenna Type	Frequency (Hz)	Injected Signal (dBm)	Antenna Gain (dB)	Cable Losses (dB)	Pads (dB)	Measured Signal (dBm)	Calculated Signal (dBm)	Error (dB)
104 cm Rod	20000000	-20	-30.48	0.4	6	-66.43	-66.58	0.15
Biconical Vertical	35000000	-30	-27.11	2	6	-73.8	-71.5	2.3
Biconical Vertical	198000000	-30	-20.13	4.7	6	-68.6	-67.19	1.41
Biconical Horizontal	35000000	-30	-30.84	2	6	-83.6	-78.96	4.64
Biconical Horizontal	198000000	-30	-18.63	4.7	6	-65	-64.19	0.81
LPDA Vertical	290000000	-30	-15.98	2.7	6	-66.4	-66.21	0.19
LPDA Vertical	500000000	-30	-14.24	3.3	6	-70	-66.26	3.74
LPDA Horizontal	290000000	-30	-17.85	2.7	6	-66.6	-69.95	3.35
LPDA Horizontal	500000000	-30	-14.88	3.3	6	-71.5	-67.54	3.96

Table 5.5: RE102 Antenna Verification Audit

Table 5.5 shows results for spot audits of the measurements taken by the various RE102 antennas and compared to theoretically calculated values determined by Equation 5.3. While some of the errors are larger that the ±3 dB objective of MIL-STD-461G, one must also consider that since this measurement is based on a two antenna system, both sharing in the error. Also, the facilities are far from the ideal controlled and screened environment required by that standard. Therefore, overall, it appears that this audit was very successful and the antennas should be reasonably accurate for purposes of pre-compliance testing.

5.6.5 RE102 Simplified Test Protocol Design

The following is a simplified procedure for the RE102 test scanning and collection of spectrum analyser measurement data for later plotting and analysis.

The entire band of interest for RE102 is 10 kHz to 1 GHz, which requires three RBW settings as shown in Table 5.6.

Frequency Range	RBW Setting
10 kHz - 150 kHz	1 kHz
150 kHz - 30 MHz	10 kHz
30 MHz - 1 GHz	100 kHz

Table 5.6: RE102 RBW settings

However, each complete RE102 scan will be made up of three partial scans using three different electric field measurement antennas.

The spectrum analyser settings required will include:

- Start and Stop Frequencies should be set as per the details above.
- Select the appropriate RBW for the Frequency Range as per Table 5.6.
- The VBW should either be disabled or set to its maximum frequency.
- The spectrum analyser's input attenuator should be set to AUTO.
- the spectrum analyser's pre-amplifier should be set to ON.
- Select the amplitude units to "dBμV".
- Select an appropriate amplitude scale and reference level to frame the signal measured
- Connect a USB memory stick if required to capture data files

The RE102 Test Setup of Figure 3.4 should be assembled. The general layout of this test configuration is as per CE102, except that both LISNs' measurement ports are terminated in 50 Ω. The power lines to the inputs of the LISNs should not be connected until all grounds are verified as connected.

a. The 104 cm Rod Antenna placed at 1 m from the centre of the test table setup in accordance with Figure 2.26. This scan will cover a frequency range of 10 kHz to 30 MHz in two parts, one from 10 kHz to 150 kHz with an RBW of 1 kHz and one from 150 kHz to 30 MHz with an RBW of 10 kHz.

b. The Biconical Antenna placed at 1 m from the centre of the test table setup in accordance with Figure 2.27. This scan will cover a frequency range of 30 MHz to 200 MHz with an RBW of 100 kHz. Two separate scans are required, one with Horizontal Polarisation and one with Vertical Polarisation.

c. The LPDA Antenna placed at 1 m from the centre of the test table setup, similarly to the Biconical Antenna arrangement above. However, the 1 m spacing is from the nose of the LPDA to the centre of the test table setup. This scan will cover a frequency range of 200 MHz to 1 GHz with an RBW of 100 kHz. Two separate scans are required, one with Horizontal Polarisation and one with Vertical Polarisation.

Each scan should follow the following process as much as possible.

1. Verify that the test table ground plane is connected to ground.
2. Verify that the supply end of the power input leads are disconnected from the supply.
3. Connect only the screen of the input power leads to the ground stud on the LISNs' input side.
4. Connect only the screen of the output power leads to the ground stud on the LISNs' output side.
5. Connect the output power leads to the LISNs' output jacks.
6. Verify that the power supply is setup to provide 115 VAC and then verify that it is switched off.
7. Connect the input power leads to the input jacks of the LISNs.
8. Connect the output power leads to the EUT power input socket.
9. Connect the measurement lead from the spectrum analyser to the correctly placed RE102 measurement antenna, via a 6dB attenuator.
10. Connect the output power leads to the EUT power input socket.
11. Use the spectrum analyser to take a scan of the ambient electric field noise and save the data (.CSV format preferred) with an appropriate name.
12. Turn on the AC mains supply.
13. Turn on the EUT, if it is separately switched.
14. Use the spectrum analyser to take a scan of the electric field strength and save the data (.CSV format preferred) with an appropriate name.
15. Turn off the EUT and the AC mains supply and repeat for all measurement antennas and polarisations from Step 9.

The resulting .CSV files are then opened with a spreadsheet program such as OpenOffice Spreadsheet or Microsoft Excel. The data for the for the specific antennas and polarisations should be concatenated and X-Y Scatter Diagram charts should be created with a logarithmic Frequency axis (in Hz) and linear Measured Level (in dBμV/m) axis. The raw measured level column of the .CSV file, should be adjusted using the calibration curves of Sections 5.6.1.1, 5.6.2.1, 5.6.3.1, for the respective measurement antennas.

These levels should then be compared to the limits line of Figure 2.25, which can also be plotted to provide an easily readable indication of any areas of concern. Any peaks found to be within 3 dB of the limit or above should be tabulated as emissions of concern.

5.7 Summary of Pre-compliance Test Design

This chapter has drawn on the technical parts of the Literature Review of Chapter 2 and the second half of the Methodology of Chapter 3 to develop an almost complete treatment for the MIL-STD-461G pre-compliance testing. This was done in support of determining a suitable, reduced-cost and practical EMI pre-compliance test for COTS equipment for insertion into a military environment, such as a submarine combat system.

The design was undertaken of a practical facility layout and selection of materials for the development of such a test facility approximating, as closely as possible, a formal test environment. The design of individual EMI sensors was developed based on well documented standard designs and some established theory. Part of their development was the selection of low-cost, practically available materials as alternatives to the original legacy designs. Further drawing on the the established theory, these sensors were calibrated and tested using experimental techniques to verify their function and suitability for supporting pre-compliance testing.

As well, the development of individual, detailed pre-compliance test procedures for each relevant MIL-STD-461G requirement was undertaken with attention to electrical safety. These are proposed as a reference set of simplified, practical and relatively low-cost emissions test protocols which may be applied to COTS equipment with the aim of closing identified compliance gaps with military requirements.

It should be noted that the entire budget for materials, cables, adapters and components was about $1000, $275 of which was the ground plane material. The construction and calibration labour took approximately two man weeks. While it may be expected that an OEM or system developer would already have signal generators and spectrum analysers as part of their test equipment inventory, a once-off procurement of approximately $5000 should provide suitable test equipment as was used for this project.

Chapter 6

Protocol Verification

This chapter walks through the experimental execution of the pre-compliance testing protocols presented in Chapter 5 to verify their viability as a means of identifying EMC compliance gaps. This experimental testing also draws on the facilities, test equipment and sensors procured, adapted and constructed as a result of the activities of Chapter 5.

The following pre-compliance test should incorporate the verification of the respective test sensor systems, but does not elaborate them as they are essentially a duplicate of those demonstrated in Chapter 5. As well, in the interests of brevity, the RE102 intermediate results, such as for each individual antenna and its polarisations, are not shown individually. However, their integrated results are disclosed in Section 6.6.7, critically compared to the respective MIL-STD-461G limits.

Any risks associated with the experimental content of this chapter have been previously analysed and the appropriate controls have been applied in accordance with the Hazard Risk Analysis of Appendix D.

6.1 General Test Setup and EUT

The general test setup is approximated, based on the MIL-STD-461G general test setup, illustrated in Figure 3.4. This configuration is shown in Figure 6.1. Here, the equipment under test or EUT is seen to the left.

Figure 6.1: General Setup of the test table. Note that it is actually setup for CE101 with the current clamp on Line 1 (LISN 1).

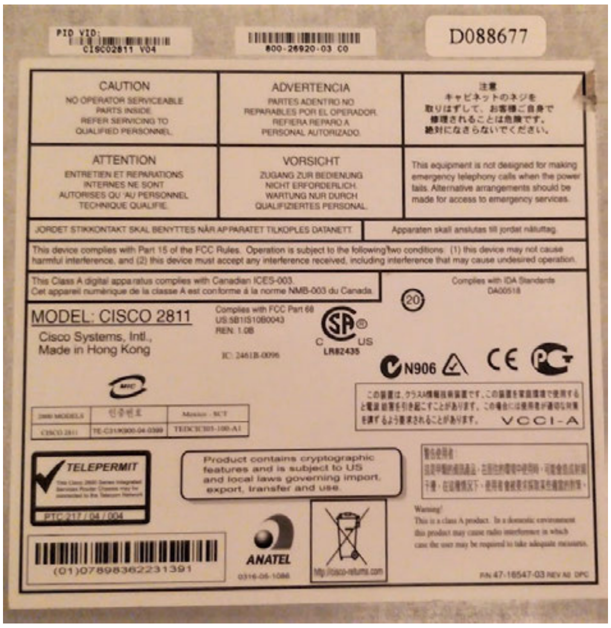

Figure 6.2: Equipment Under Test: CISCO 2811 Switch/Router compliance plate. As can be seen, this device carries many commercial EMI certifications, including an FCC statement, C-tick, and CE marks. A very typical piece of professional COTS ICT equipment.

The EUT selected for this verification is a CISCO 2811 Network Switch/Router. The compliance plate for this EUT is shown in Figure 6.2. As can be seen, this device carries many commercial EMI certifications, including an FCC statement, as well as C-tick and CE marks. It is representative of a very typical piece of professional COTS ICT equipment, likely to be appealing to combat system designer.

The measurement and recording equipment, shown in Figure 6.3. consists of:

- A SIGLENT SSA3021X 9 kHz to 2.1 GHz Spectrum Analyser,
- A Signal Hound SA44B USB based 1 Hz to 4.4 GHz Spectrum Analyser (not seen as it was hidden behind other instruments),
- An ASUS ZenBook laptop PC, running SIGLENT *EZY-Spectrum* and Signal Hound *SPIKE* software,
- An ACER external PC monitor,
- A HP3325B Synthesiser/Function Generator to generate lower frequency verification signals, and
- A HP8640B RF Signal Generator to generate higher frequency verification signals.

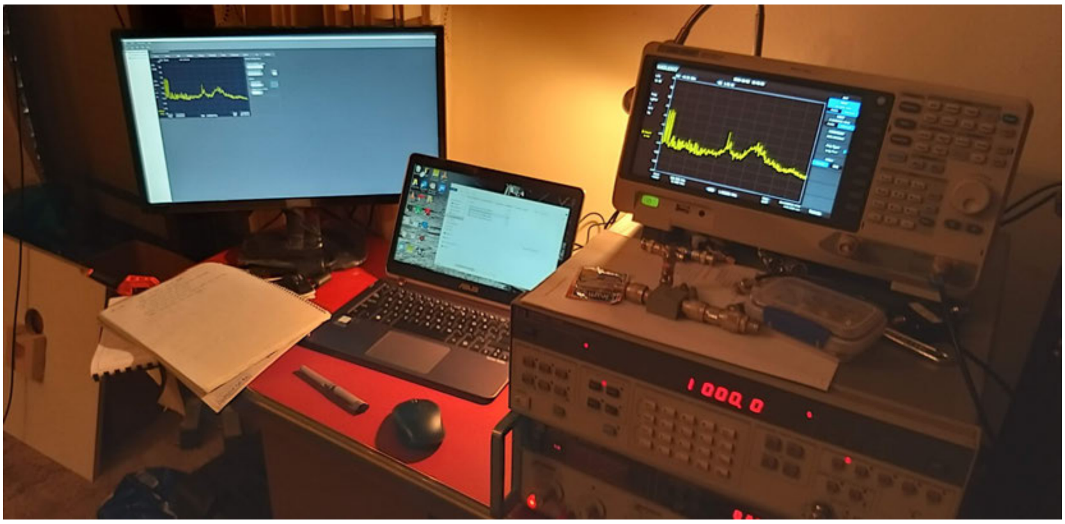

Figure 6.3: Measurement and Recording Equipment

6.2 Common Configuration and Initial Steps

There are several common items of test configuration and initial test steps that, while critical to individual test execution, call on much unnecessary duplication of procedure between the individual tests. To minimise this inconvenience, since the complete suite of pre-compliance tests were to be executed in sequence, it was determined to configure the common items of test configuration once, for all testing.

The following steps are common to the CE101, CE102, RE101 and RE102 simplified test protocols of Chapter 5. It is this common portion of the test protocols that were determined to be executed once at the start of all testing.

1. Verify that the test table ground plane is connected to ground.
2. Verify that the supply end of the power input leads are disconnected from the supply.
3. Connect only the screen of the input power leads to the ground stud on the LISNs' input side.
4. Connect only the screen of the output power leads to the ground stud on the LISNs' output side.
5. Connect the output power leads to the LISNs' output jacks.
6. Verify that the power supply is setup to provide 115 VAC and then verify that it is switched off (Figure 6.4, shows the verification of the mains voltage at the output of the LISNs).
7. Connect the input power leads to the input jacks of the LISNs.
8. Connect the output power leads to the EUT power input socket.

Figure 6.4: Verification of correct mains voltage at the output of the LISNs.

6.3 CE101 Test Protocol Verification

After the execution of the common items of test configuration and initial test steps of Section 6.2, above, continue from Step 9 of the CE101 Simplified Test of Section 5.3.4.

6.3.1 CE101 Test Setup

Figure 6.5, shows the test setup of the current clamp about 5 cm from the LISN output for the CE101 test of AC Line 1 through LISN1 (left LISN unit). The complete test also required that AC Line 2 be measured through LISN2 (right LISN unit).

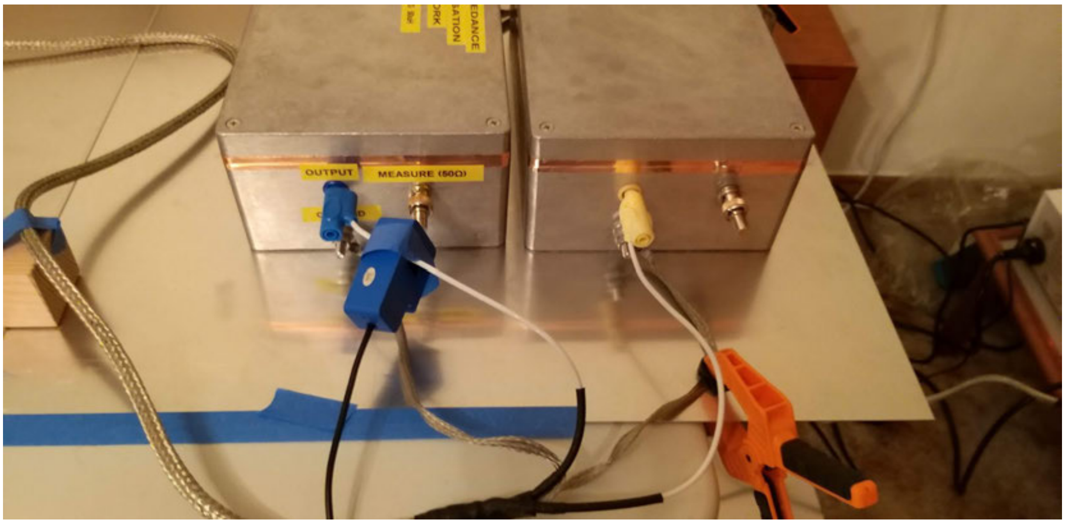

Figure 6.5: CE101 Test Setup. Line 1 (LISN 1) has the current sensor attached.

6.3.2 CE101 Test Execution and Results

The Signal Hound spectrum analyser was required as the measurement device due to the low frequencies involved. It was configured as per the directions of Section 5.3.4 and the test data was captured in .CSV format for each RBW range.

This data was concatenated and the calibration data of Figure 5.15 was applied to adjust the measured values to actual figures in dBμA, as shown in the result for Line 1 in Figure 6.6.

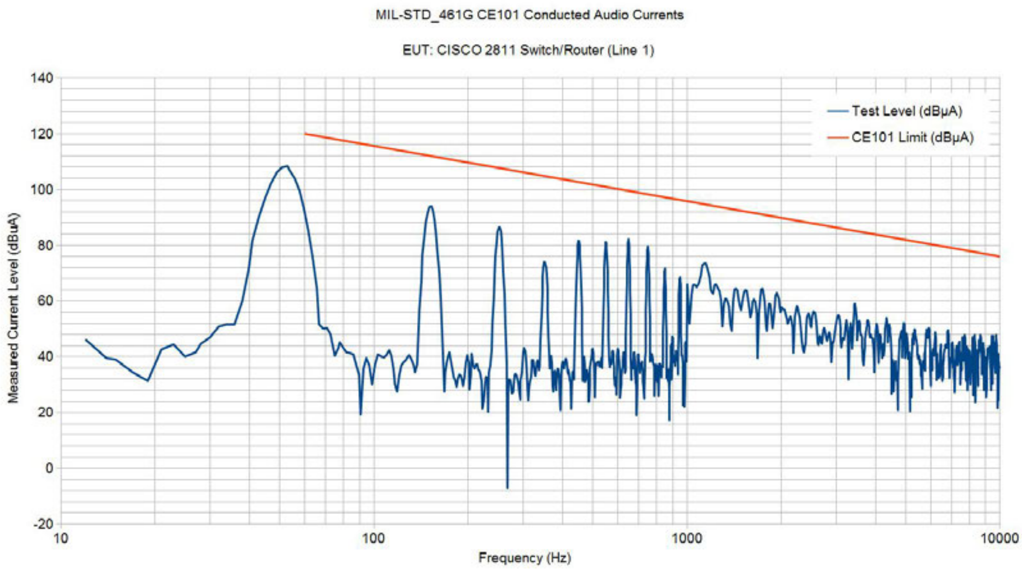

Figure 6.6: CE101 Test Result - Line 1 and Line 2 were identical, only Line 1 shown

The data collected and adjusted for Line 2 was essentially identical. As seen in Figure 6.6, there are no injected current emissions of concern against the CE101 limit line.

The simplified test protocol of Section 5.3.4 for CE101 was verified successfully.

6.4 CE102 Test Protocol Verification

After the execution of the CE101 test, the common items of test configuration and initial test steps of Section 6.2 remain current and in place. Therefore, the Steps for CE102 continue from Step 9 of the CE102 Simplified Test of Section 5.4.2.

6.4.1 CE102 Test Setup

Figure 6.7, shows the test setup for the CE102 test of AC Line 1 through the LISN1 measurement port (left LISN unit) connected to the spectrum analyser via the transient suppressor and 20 dB attenuator. The complete test also required that AC Line 2 be measured through LISN2 (right LISN unit).

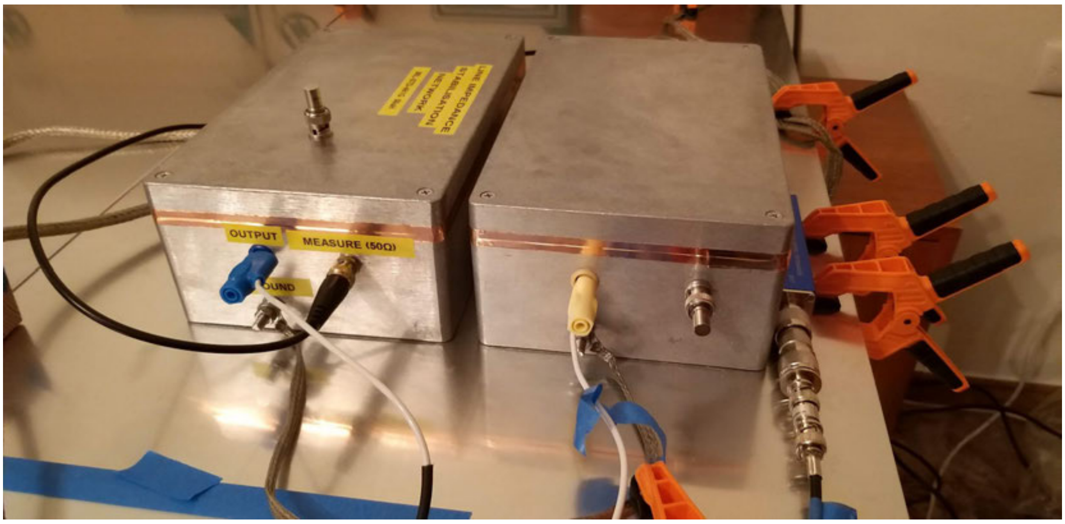

Figure 6.7: CE102 Test Setup - LISN 1 has the measurement port connected to the spectrum analyser via transient suppressor and 20 dB attenuator (seen on the right of LISN 2.

6.4.2 CE102 Test Execution and Results

As it and its PC software was already operating, it was convenient to use the Signal Hound spectrum analyser as the measurement device. It was reconfigured as per the directions of Section 5.4.2 and the test data was captured in .CSV format for each RBW range.

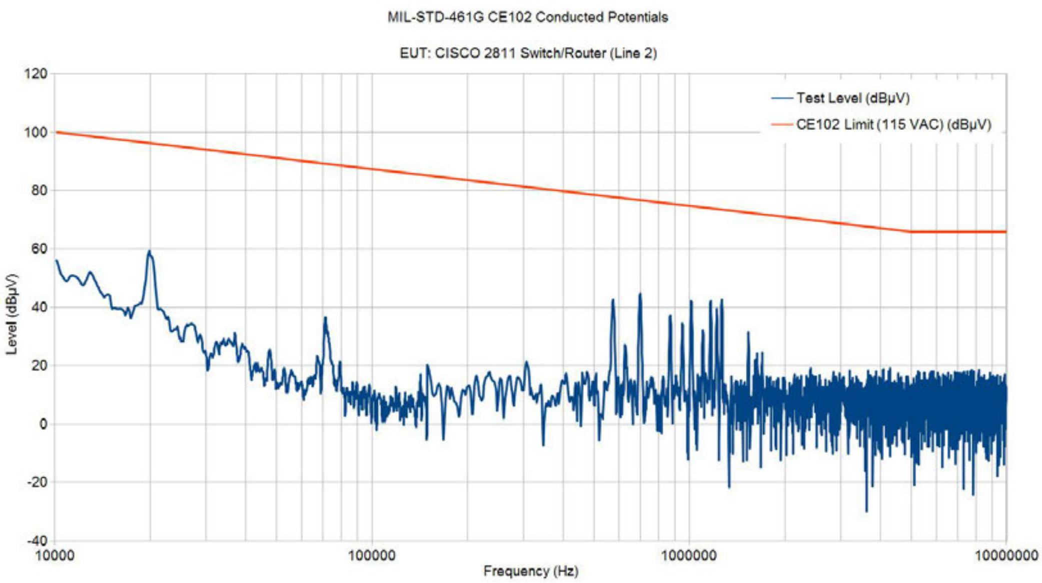

Figure 6.8: CE102 Test Result. Both Line 1 and Line 2 were again identical, only Line 2 shown

This data was concatenated and the LISN calibration data of Figure 5.8 was applied to adjust the measured values to actual figures in dBμV, as shown in the result for Line 2 in Figure 6.8.

The data collected and adjusted for Line 1 was essentially identical. As seen in Figure 6.8, there are no voltage emissions of concern against the CE102 limit line.

The simplified test protocol of Section 5.4.2 for CE102 was verified successfully. Of interest, artefacts of the local AM broadcast signals can be seen between 500 kHz and approximately 1.5 MHz. There was also a 20 kHz tone seen. However, its source is unknown as it remains there when the EUT is turned off. There was also evidence of a signal just over 70 kHz, the source of which becomes evident in the following RE101 test.

6.5 RE101 Test Protocol Verification

After the execution of the CE102 test, the common items of test configuration and initial test steps of Section 6.2 remain current and in place. Therefore, the Steps for RE101 can continue from Step 9 of the RE101 Simplified Test of Section 5.5.4.

6.5.1 RE101 Test Setup

Figure 5.33, shows the detailed sensor placement, at 7 cm between the centreline across the loop to the face of the EUT. Note that the EUT was lifted so that it is at height roughly centred through the diameter of the RE101 Magnetic Field Sensor loop.

6.5.2 RE101 Test Execution

Conveniently, the Signal Hound spectrum analyser was again required as the measurement device due to the low frequencies involved. It was reconfigured as per the directions of Section 5.5.4.

The test execution of RE101 requires exploratory scans to be made all around the EUT. Firstly, to determine if there were any ambient magnetic field components which may affect test readings. Secondly, with the EUT energised, to identify any specific zone or zones where any detected emissions reach a peak.

No ambient signals of concern were found after a complete exploration all around the EUT. However, with the EUT energised, it was found that a major component at 73 kHz was prevalent toward the front of the EUT.

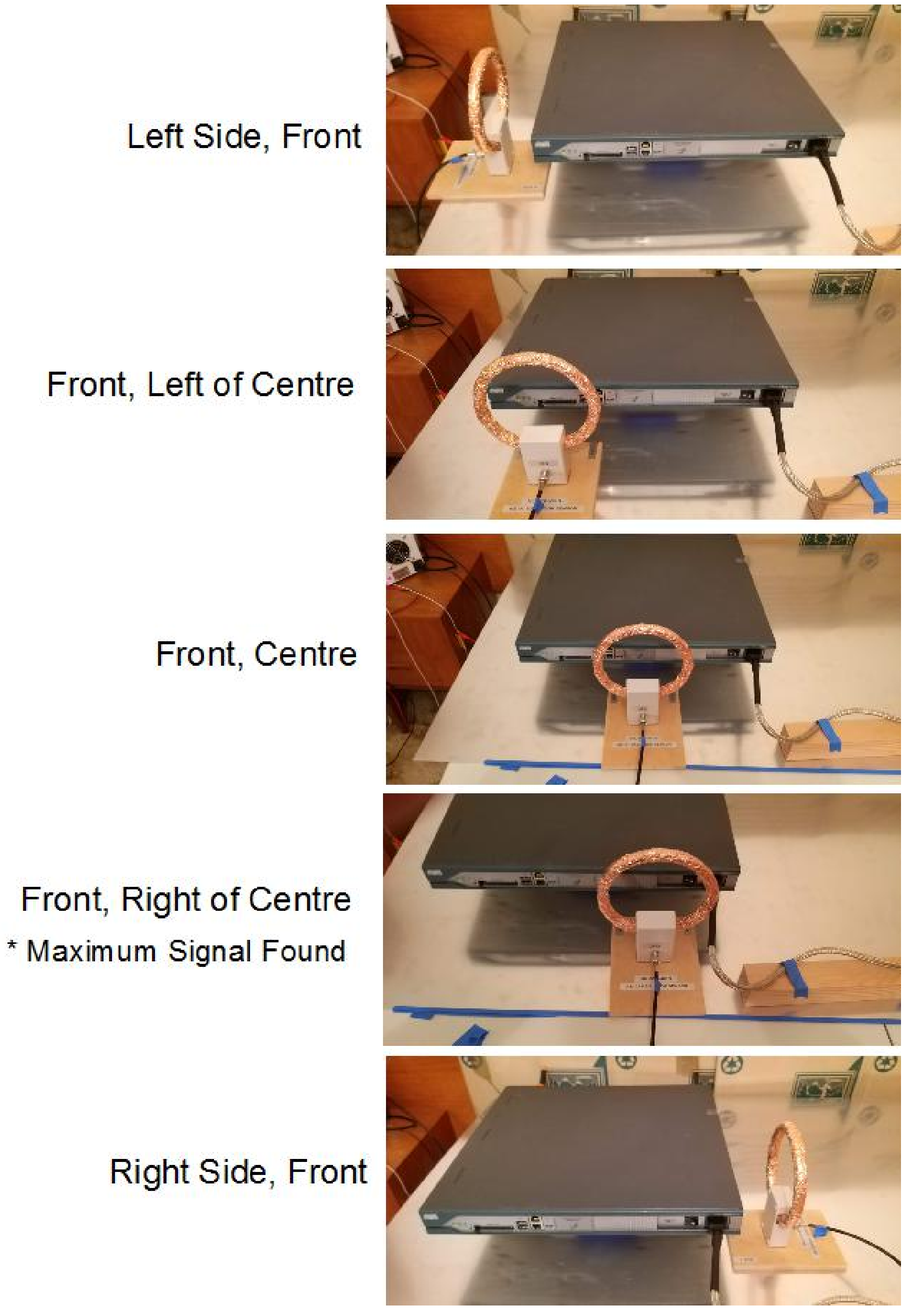

Figure 6.9: RE101 exploratory scanning - searching for the position which returns the highest level measurement.

Figure 6.9 shows the some of the steps involved in the exploratory scanning of the energised EUT. As can been, the strongest signal was detected at the Front, Right of Centre position.

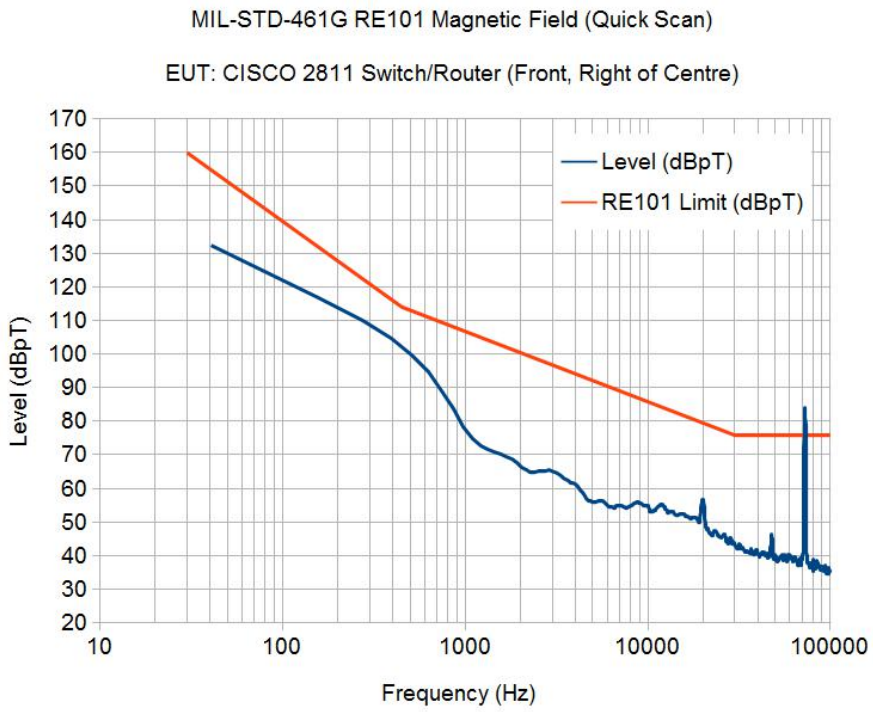

Figure 6.10: Example, RE101 full-band exploratory scan. This scan was taken at the Front, Right of Centre position, which appeared to be position yielding the highest reading.

It was found useful to reconfigure the spectrum analyser to cover the entire RE101 frequency range at an RBW of 10 kHz for purposes of exploration. Figure 6.10 shows a such a scan for the position that produced the highest reading.

The setting of the RBW to 10 kHz allowed the spectrum analyser to scan quickly, facilitating a relatively easy balance between accuracy and movement of the sensor to zero in on the position of highest reading.

It was verified, by another exploratory pass, that the 73 kHz component discovered was the only significant reading. Therefore, only one "official" RE101 scan was required at the Front, Right of Centre position.

6.5.3 RE101 Test Results

The spectrum analyser was reconfigured as per the directions of Section 5.5.4 and the test data was captured in .CSV format for each RBW range, with the sensor placed at the Front, Right of Centre position, 7 cm from the face of the EUT.

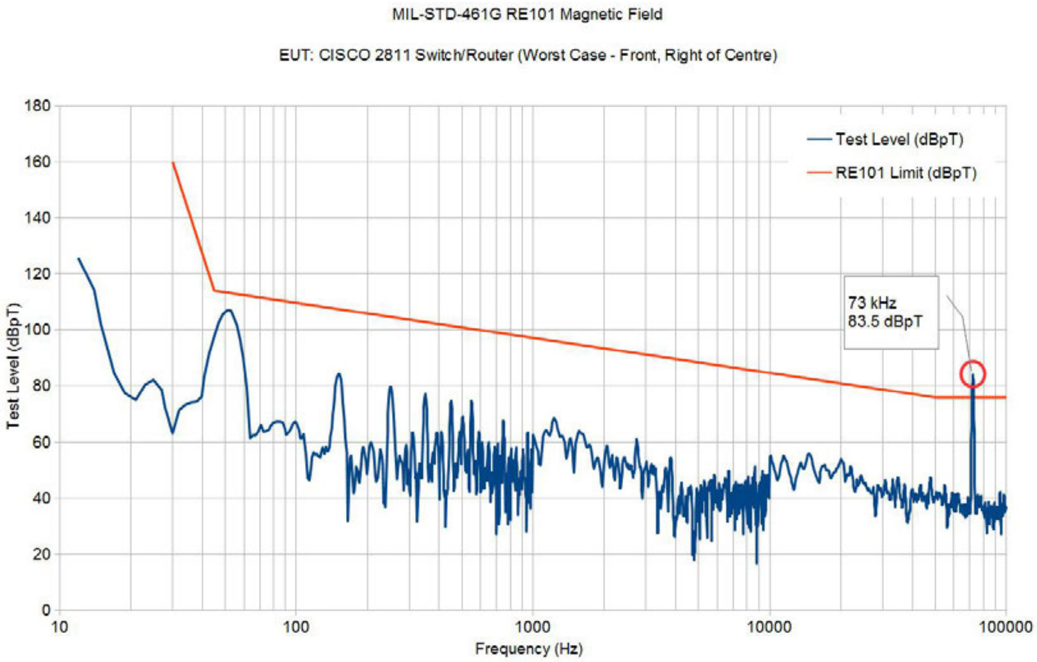

Figure 6.11: RE101 Final Result. There is one outage found at the Front, Right of Centre of approximately 7.5 dB at 73 kHz.

This data was concatenated and the RE101 magnetic sensor loop calibration data of Figure 5.32 was applied to adjust the measured values to actual figures in dBpT, as shown in Figure 6.11.

The simplified test protocol of Section 5.5.4 for RE101 was verified successfully.

There was an "outage" identified of 7.5 dB at a frequency of 73 kHz, which reaches its peak just right of centre on the front of the EUT. This is an example of COTS equipment baring commercial certifications, but not meeting MIL-STD-461G requirements. depending on how this equipment is housed in a military application, there is a risk of a non-compliance being recorded in a formal qualification test.

6.6 RE102 Test Protocol Verification

After the execution of the RE101 test, the common items of test configuration and initial test steps of Section 6.2 remain current and in place. Therefore, the steps for RE102 can continue from Step 9 of the RE102 Simplified Test of Section 5.6.5.

The SIGLENT SSA3021X was selected at the measurement instrument, connected to the ASUS PC running EZY-Spectrum software which was convenient for capturing scans directly on the PC.

As identified in Section 5.6, the RE102 testing requires three different antennas as well as separate vertical and horizontal polarisations. The following sections describe the placement and orientation of these respective antennas, the frequency ranges scanned and

6.6.1 RE102 Test Setup (104 cm Rod Antenna)

Figure 6.12, shows the placement of the 104 cm Rod Antenna for the RE102 test. Unlike the biconical and LPDA antennas, the rod antenna on has the one polarisation and is the same for the Horizontal and Vertical Polarisation scans.

Figure 6.12: RE102 Test Setup for the 104 cm Rod Antenna. This test covers the frequency range of 10 kHz to 30 MHz and is the same for both Horizontal and Vertical Polarisation scans.

6.6.2 RE102 Test Execution and Results (104 cm Rod Antenna)

The rod antenna is used for scans from:

- 10 kHz to 150 kHz with an RBW of 1 kHz, and
- 150 kHz to 30 MHz with an RBW of 10kHz.

Scans for both Ambient (EUT off) and Test (EUT on) when taken. The Ambient scans used the MAX-HOLD feature of the spectrum analyser to capture ambient transitory signals to verify that any measured EUT emissions were not actually external interference. The test data was captured in .CSV format for each frequency range.

No electric field emissions from the EUT of concern were observed.

6.6.3 RE102 Test Setup (Biconical Antenna)

Figure 6.13, shows the placement of the Biconical Antenna for the RE102 test. Unlike the Rod Antenna, the Biconical Antenna is used for both Horizontal and Vertical Polarisation scans.

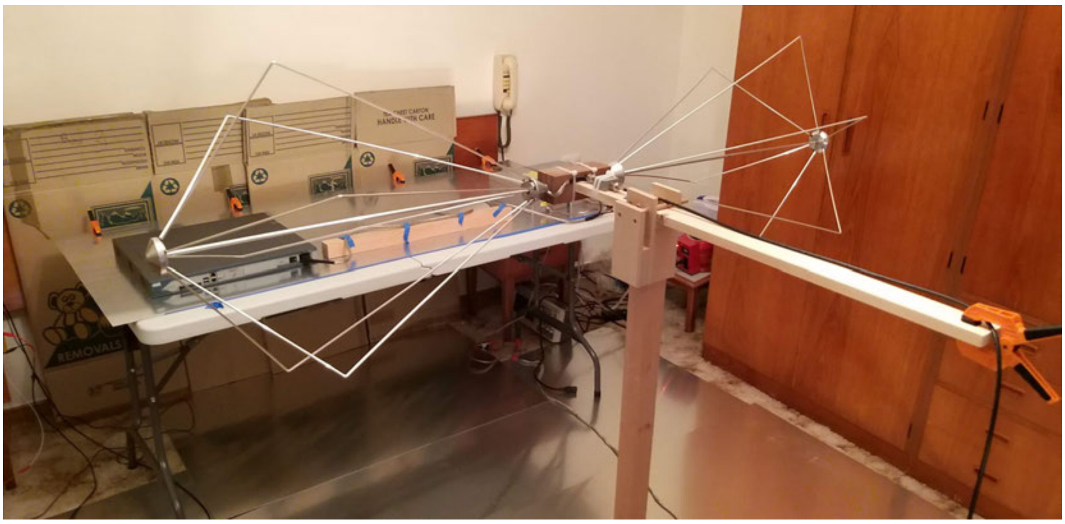

Figure 6.13: RE102 Test Setup for the Biconical Antenna. Horizontal Polarisation shown. This test covers the frequency range of 30 MHz to 200 MHz and is run for both Horizontal and Vertical Polarisation.

6.6.4 RE102 Test Execution and Results (Biconical Antenna)

The Biconical Antenna is used for scans from 30 MHz to 200 MHz with an RBW of 100 kHz.

Scans for both Ambient (EUT off) and Test (EUT on) when taken. The Ambient scans used the MAX-HOLD feature of the spectrum analyser to capture ambient transitory signals to verify that any measured EUT emissions were not actually external interference. The test data was captured in .CSV format for each frequency range.

No electric field emissions from the EUT of concern were observed. Supplementary scans were undertaken with the top cover removed from the EUT. No new emissions were detected.

6.6.5 RE102 Test Setup (LPDA Antenna)

Figure 6.14, shows the placement of the LPDA Antenna for the RE102 test. As with the Biconical Antenna, the LPDA Antenna is used for both Horizontal and Vertical Polarisation scans.

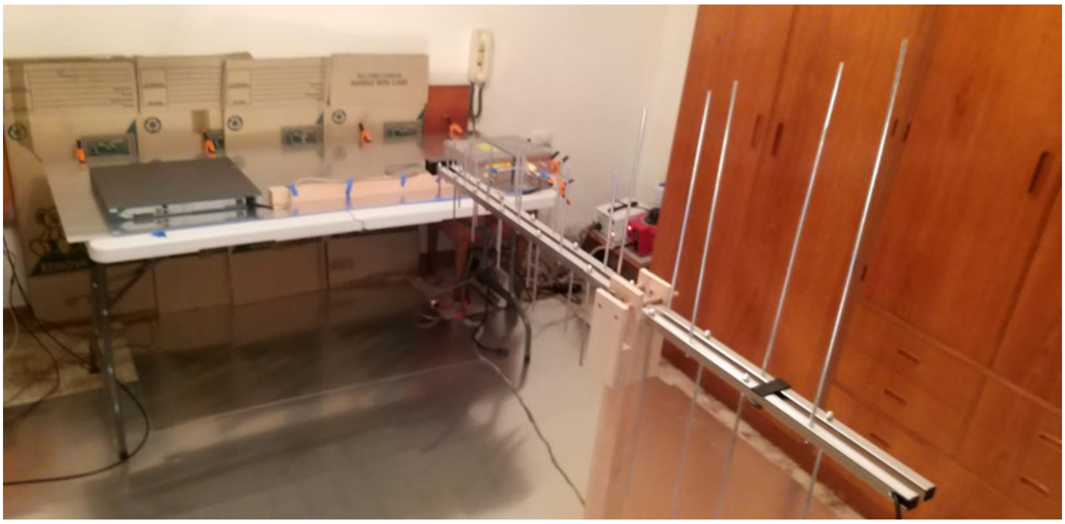

Figure 6.14: RE102 Test Setup for the LPDA Antenna. Vertical Polarisation shown. This test covers the frequency range of 200 MHz to 1 GHz and is run for both Horizontal and Vertical Polarisation.

6.6.6 RE102 Test Execution and Results (LPDA Antenna)

The LPDA Antenna is used for scans from 200 MHz to 1 GHz with an RBW of 100 kHz.

Scans for both Ambient (EUT off) and Test (EUT on) when taken. The Ambient scans used the MAX-HOLD feature of the spectrum analyser to capture ambient transitory signals to verify that any measured EUT emissions were not actually external interference. The test data was captured in .CSV format for each frequency range.

No electric field emissions from the EUT of concern were observed. Supplementary scans were undertaken with the top cover removed from the EUT. No new emissions were detected. Only in the Vertical Polarisation were new emissions detected. These are detailed in Section 6.6.7.3.

6.6.7 RE102 Integrated Results

The .CSV files for each individual scan were collated into three groups.

1. Horizontal Polarisation,
2. Vertical Polarisation, and
3. Supplementary Vertical Polarisation.

For each group, a spreadsheet was created to concatenate the individual antenna scans for Ambient and Test results and to apply the appropriate calibration curves (Antenna Factors) as developed in Chapter 5. A chart was created showing the complete spectral scan for the RE102 frequency range, showing the Test scan super imposed on the Ambient scan as well as the RE102 limit line.

Group 1, Horizontal Polarisation is shown in Figure 6.15; Group 2, Vertical Polarisation is shown in Figure 6.16; and Group 3, the supplementary Vertical Polarisation scan is shown in Figure 6.17.

6.6.7.1 RE102 Integrated Result (Horizontal Polarisation)

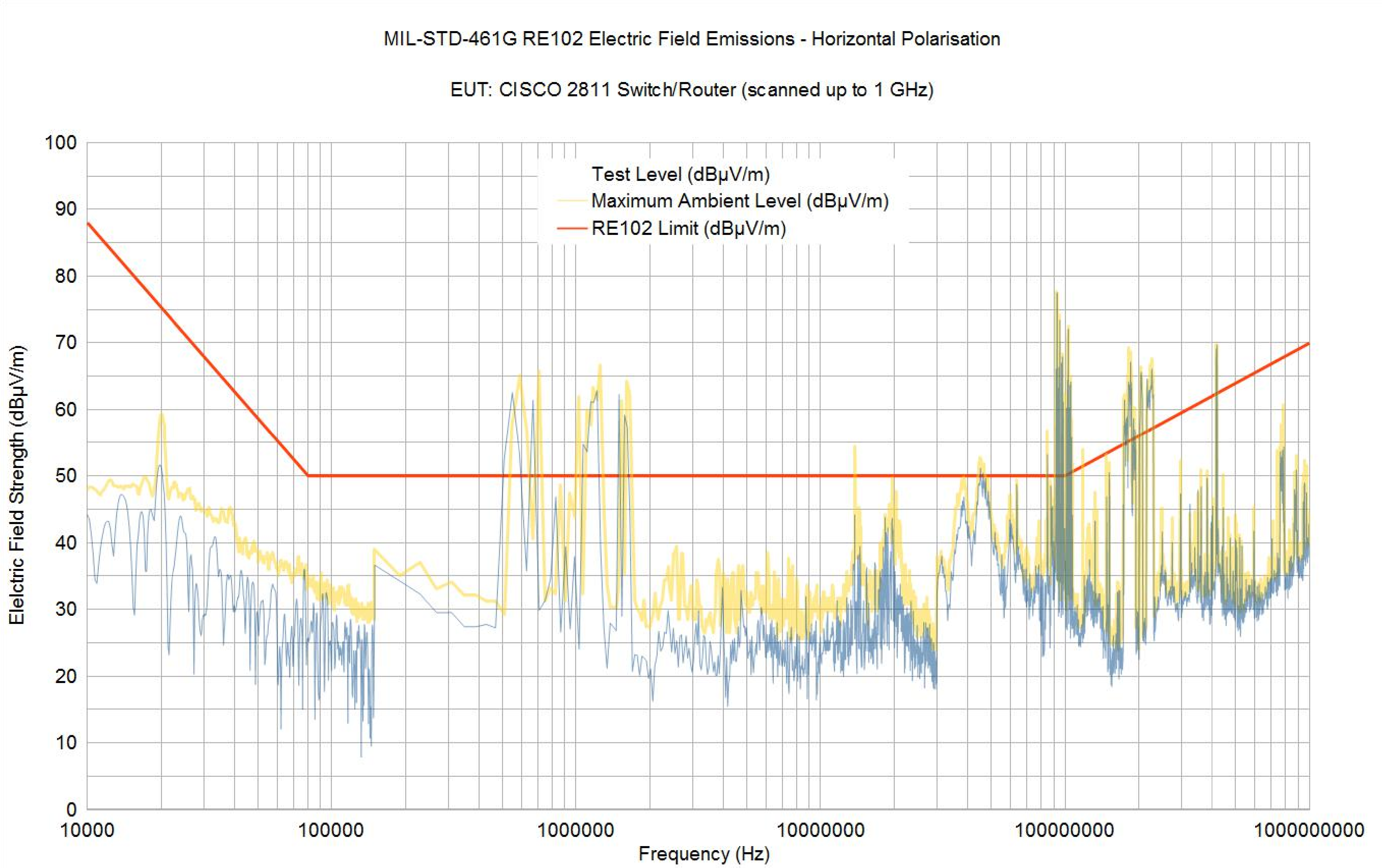

Figure 6.15: RE102 - Integrated Result for Horizontal Polarisation

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6.6.7.2 RE102 Integrated Result (Vertical Polarisation)

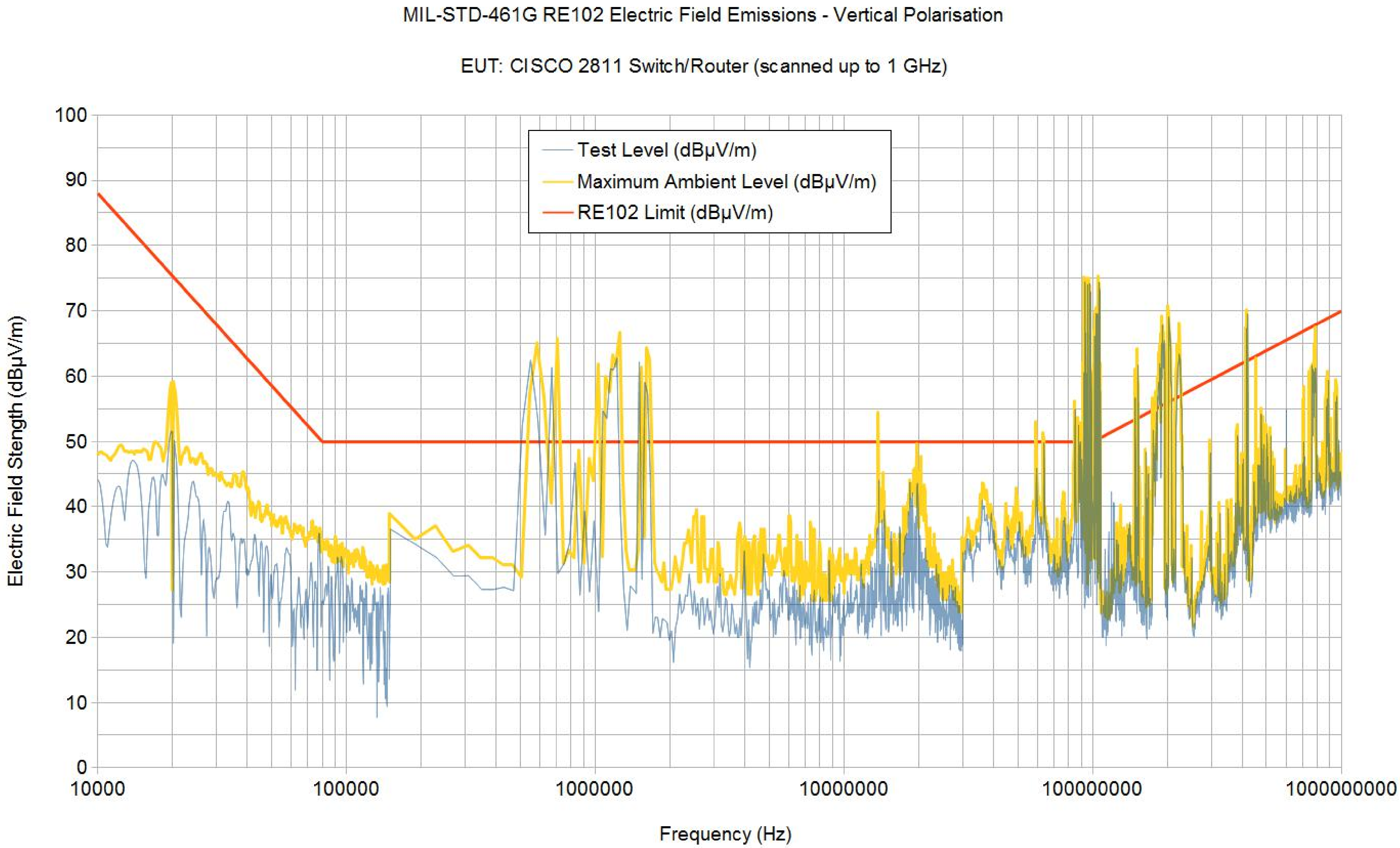

Figure 6.16: RE102 - Integrated Result for Vertical Polarisation

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6.6.7.3 RE102 Integrated Result (Supplementary Vertical Polarisation)

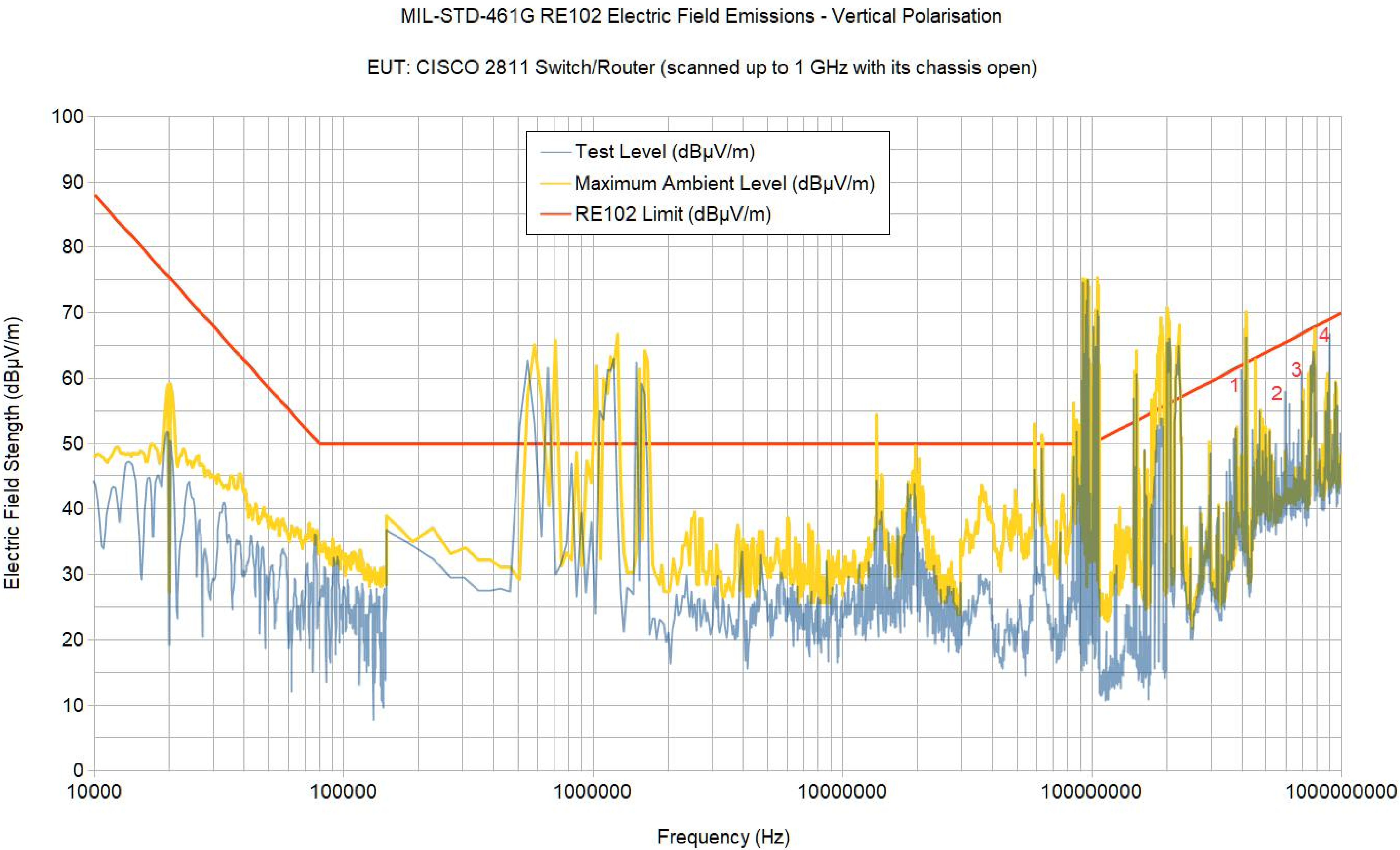

Figure 6.17: RE102 - Supplementary Integrated Result for Vertical Polarisation. This scan shows the electric field emissions measured with the top cover removed from the EUT.

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6.6.8 Summary of RE102 Test Results

The normal Horizontal and Vertical scans did not detect any emissions attributable to the EUT.

Even the supplementary scan with the top cover removed from the EUT, there were no test emissions measured beyond the RE102 limit line, however, several emissions, numbered 1 to 4, between 400 MHz and 900MHz were identified running very close to it. As these emissions are not measured under the normal operating configuration of the EUT, so they are not considered emissions of concern.

This scan was only supplementary as a trial to demonstrate that the RE102 pre-compliance test would detect some emissions are purely to exercise the intention of the scan.

The simplified test protocol of Section 5.6.5 for RE102 was verified successfully.

However, it must be pointed out that the RE102 scans show considerable interference from the AM and FM broadcast bands, as well at the TV broadcast bands and some other components that breached the limit line in the ambient scans. These areas, as previously mentioned, could potentially disguise test emissions. Ultimately, the facility used for this project was not ideal and a better, lower noise facility should be considered for such measurements.

6.7 Summary of Test Results

Table 6.1 provides a summary of results for the MIL-STD-461G Pre-compliance test for the EUT, a CISCO 2811 Network Switch/Router.

MIL-STD-461G Requirement	**Compliance**	**Comment**
CE101	COMPLIANT	No emissions of concern detected
CE102	COMPLIANT	No emissions of concern detected
RE101	NON-COMPLIANT	One outage of 7.5 dB at 73 kHz
RE102	COMPLIANT	No emissions of concern detected

Table 6.1: Summary of results of MIL-STD-461G Pre-compliance Test

It was found that the EUT was compliant to MIL-STD-461G in all areas except for one magnetic field outage. As this was a near-field test, it is entirely possible that this piece of equipment could be shielded or separated from other equipment such that this particular emission would be of no concern.

6.8 Summary of Protocol Verification

This chapter worked through the complete set of simplified pre-compliance test protocols as developed in Chapter 5. Each protocol was exercised successfully.

It was stated that since the entire suite of tests would be run, there was scope for streamlining repetitive setup reconfiguration and some initial steps which are common to all tests. These were presented and executed.

The outcome of this test run was that the protocols presented in Chapter 5 were run successfully in an approximated test facility with low cost componentry. Therefore, they were verified as viable as a low investment, MIL-STD-461G pre-compliance testing of COTS equipment intended for insertion into a military environment, such as a submarine combat system.

Chapter 7

Conclusions and Further Work

7.1 Conclusions

The overarching intention of this project was to verify that COTS equipment could not be inserted into military systems without risk of both EMI non-compliance to military standards and potentially, its acceptance into service.

Chapter 1 stated the project aim to be essentially in two parts.

1. To determine potential compliance gaps between typical military EMI standards and those of typical COTS equipment items in order to ascertain risks of non-compliance.
2. To develop of a reference set of low-cost and practical test protocols that may facilitate the identification of any specific compliance risks of such equipment.

Both of these aims have been achieved.

The gap analysis of Chapter 4 has directly addressed the first aim by clearly identifying the compliance gaps between the predominant commercial and military EMI standards. Table 4.14, clearly summarises that the predominant commercial EMI standards of COTS equipment are non-compliant with the predominant military EMI standard. This finding also consolidated the need for the second project aim.

As it was established that commercial EMI standards cannot be read across to a corresponding military standard to prove compliance, it was determined that an appropriate course of action would be to re-qualify such COTS equipment to the military standard. However, this was established to be an expensive and time consuming exercise. Hence, a more intermediate, cost and time effective course of action would be to use pre-compliance techniques to quantify the EMI performance of such equipment so that the OEM could take appropriate design action to mitigate any risk areas found.

The pre-compliance test protocol design of Chapter 5 and the protocol verification of Chapter 6 directly address the second project aim. This is achieved by clearly demonstrating the development of a reference set of low-cost and practical, pre-compliance test protocols that can facilitate the identification of any specific compliance risks of COTS equipment. The viability of this technique was proven, up to a frequency limit of 1 GHz, through the experimental testing undertaken in the protocol verification.

In terms of meeting the objectives of the Project Specification at Appendix A, the following conclusions are presented for these objectives.

1. Research elements of EMC design in the military environment (such as in a submarine).

   The literature review of Chapter 2, Section 2.3, directly address this objective and, through research, develops the theory used in the methodology, gap analysis, protocol design and verification. Section 2.4.3 elaborates the application of EMI theory and design into the military environment of a submarine.

2. Research the motivation for COTS equipment insertion into such a military environment.

   The literature review of Chapter 2, Section 2.2, directly addresses this objective and, through research, develops an historical, political, economical and ultimately technical basis for the motivation to use COTS in the military environment.

3. Determine the subset of electromagnetic interference (EMI) emissions limits and tests as applicable to (non-radio) equipment in such a military environment.

   The literature review of Chapter 2, Sections 2.4, directly address this objective by researching the key differences between commercial EMI qualifications and those demanded by the military. It goes on to determine the appropriate EMI standard, requirements and limits applicable to non-radio equipment in the submarine environment. This sets the predominant military requirements to which the following gap analysis compares commercial EMI standards.

4. Research the suitability of COTS equipment in respect to EMC compliance in such a military environment.

   The gap analysis of Chapter 4 partially addresses this objective by clearly showing that the commercial EMI standards, to which most COTS equipment is certified to meet, are not compliant to the military requirements established in the literature review. The gap analysis then draws the conclusion that COTS equipment may be reasonably suitable for military use but there is no proof provided by its commercial certifications.

   The pre-compliance test protocols of Chapter 5 and protocol verification of Chapter 6 provides experimental evidence that the representative EUT used is suitable for potential use in the military environment. This demonstrates that the suitability of COTS equipment must be determined by measurement.

5. Determine suitable, reduced-cost and practical EMI pre-compliance testing configurations.

   The methodology of Chapter 3, Section 3.3 and the pre-compliance test protocol design of Chapter 5 both address this requirement in two stages. The methodology analyses the use of facilities, measurement equipment, sensor theory, operation and calibration. The pre-compliance test protocol design implements the framework provided by the methodology to design, construct, calibrate and verify reduced-cost and practical EMI pre-compliance testing configurations.

6. Develop a proposed reference set of simplified, practical and relatively low cost radiated and conducted emissions test protocols which may be applied to COTS equipment with the aim of closing identified relevant military EMC compliance gaps.

   As established in the previous objective, the methodology of Chapter 3, Section 3.3 and the pre-compliance test protocol design of Chapter 5 both address this requirement. The protocol verification of Chapter 6, gives experimental proof that the simplified, practical and relatively low cost radiated and conducted emissions test protocols developed may be applied to COTS equipment with the aim of closing identified relevant military EMC compliance gaps. Therefore, this objective was completely addressed within the limits of this project.

7. (Extra objective 1) Experimental testing of these protocols (applying an upper frequency limit of 1GHz) to verify the viability of the proposed tests as a means of identifying EMC design risks.

   The protocol verification of Chapter 6, as established above, has addressed this extra work objective by verifying the pre-compliance test protocol design of Chapter 5 and essentially closing the theoretical loop by experimentally demonstrating the viability of the proposed tests as a means of identifying EMC design risks.

Ultimately, it is concluded that this project has clearly demonstrated that commercially qualified COTS equipment is not necessarily compliant to military EMI standards. Also, it has been demonstrated that the low-investment EMI pre-compliance test protocols and the developed supporting equipment can be used to help de-risk COTS insertion into submarine combat systems.

7.2 Potential Changes and Further Work

7.2.1 Elimination of the Biconical Antenna

Further experimentation could be undertaken to compare the performance of the LPDA antenna and even the rod antenna with the aim of potentially eliminating the need for the biconical antenna. If the useful bandwidth of the rod antenna could be extended to up to an upper frequency of 60 MHz, and the LPDA down to 60 MHz, this could be achieved.

There is some evidence in literature that indicated that this is possible. The elimination of the biconical antenna would save considerable cost and time. However, experimentation and detailed comparisons between RE102 scans taken with the two configurations would be needed verify similar performance to make it viable.

7.2.2 A more suitable facility

As it was noted in the RE102 verification summary of Section 6.6.8, the RF noise evident in the RE102 scans was quite significant and could potentially disguise real test emissions which would devalue the entire RE102 test. Selection of a better facility, if possible, could improve this. However, some further research into effective screening techniques could provide a means of preparing a facility so that RF background noise can be brought under the limit line.

7.2.3 Use of automation to collate results

Spreadsheets were extensively used to manually collate .CSV data from measurement instruments, apply calibration correction and ultimately generate final result plots. The automation of this process could shave hours off the time it takes to provide final results. A package such as MATLAB could be used to both automate the collation and calibration adjustments as well as automatically detect outages and generate a report which can interpret the final result and well as the plot.

7.2.4 Extend experimental testing beyond 1GHz

As previously mentioned, this project was limited to an upper frequency of 1 GHz due to the cost of cables and equipment able to go much beyond that limit. Ultimately, to undertake complete pre-compliance to MIL-STD-461G, it would be necessary to extend the electric field emission testing of RE102 to 18 GHz.

While there are potentially many cost effective antenna styles that could be used to cover these frequencies, the cost of the measurement receiver or spectrum analyser is likely to be between $15000 and $20000 alone. As well as this, the cable quality and connectors required would also be markedly more expensive to operate reliably out to these frequencies. However, disruptive technological advances may well bring down the costs of the instrumentation, such as more capable SDR units, etc.

7.2.5 Comparison with certified EMI test results

The ultimate proof of concept for the pre-compliance test protocols presented in this work is a direct comparison with actual certified MIL-STD-461G test results from a certified test laboratory. This could potentially provide meaningful information for improvements to be made.

References

Agilent (1998), 'Making radiated and conducted compliance measurements with emi receivers', *Agilent Technologies* **Application Note 102**.

ANSI (2017), *American National Standard for Electromagnetic Compatibility–Radiated Emission Measurements in Electromagnetic Interference (EMI) Control–Calibration and Qualification of Antennas (9 kHz to 40 GHz)*, ANSI C63.5-2017 (Revision of ANSI C63.5-2005).

AS/NZS-CISPR-32: (2015), *AS/NZS CISPR 32:2015 Electromagnetic compatibility of multimedia equipment - Emission requirements*, SAI Global Limited and Standards Australia Limited, Sydney.

Barry, C. B. (1995), The federal acquisition reform act of 1994, Report, DEFENSE INST OF SECURITY ASSISTANCE MANAGEMENT WRIGHT-PATTERSON AFB OH.

Capps, C. (2001), 'Near field or far field?', *EDN* **46**(18), 95–99.

CEMARKING.NET (2018), 'Ce marking self-certification'.
URL: *https://cemarking.net/ce-self-certification/*

Cho, S. S. (1994), 'Emi prevention in clock-distribution circuits', *Texas Instruments* .

Dhingra, C. P. & Nara, S. (2006), Convergence and divergence between mils and cots standards "commercial off the shelf (cots) equipment" — an emc perspective, *in* '2006 9th International Conference on Electromagnetic Interference and Compatibility (INCEMIC 2006)', pp. 181–188.

Dixon, D. S. (1996), E3 concerns for the military use of commercial-off-the-shelf (cots) equipment, *in* 'Proceedings of Symposium on Electromagnetic Compatibility', pp. 537–540.

Dixon, D. S. (1997), Military use of commercial-off-the-shelf (cots) equipment: updated e3 concerns, *in* '10th International Conference on Electromagnetic Compatibility, 1997. (Conf. Publ. No. 445)', pp. 29–34.

Dixon, D. S. (1998), An emc approach that permits a relaxation of radiated electric field requirements for cots equipment aboard naval platforms, *in* '1998 IEEE EMC Symposium. International Symposium on Electromagnetic Compatibility. Symposium Record (Cat. No.98CH36253)', Vol. 1, pp. 403–409 vol.1.

DoD, U. (2001), Results of detailed comparisons of individual emc requirements and test procedures delineated in major national and international commercial standards with military standard mil-std-461e, Report, US DoD.

EC (2014), *Electromagnetic Compatibility (EMC) Directive 2014/30/EU*, Vol. 2019, European Commission.
URL: *https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/electromagnetic-compatibility_en*

FCC (1996), *Understanding the FCC regulations for computers and other digital devices*, Vol. OET BULLETIN NO. 62 of *Office of Engineering and Technology*, US Federal Communication Commission.

Friis, H. T. (1946), 'A note on a simple transmission formula', *Proceedings of the IRE* **34**(5), 254–256.

Grover, F. W. (1946), *Inductance calculations*, Van Nostrand.

Guertin, N. & Miller, R. (1998), 'A-rci—the right way to submarine superiority', *Naval engineers journal* **110**(2), 21–33.

Jackson, G. A. (1987), 'The early history of radio interference', *Journal of the Institution of Electronic and Radio Engineers* **57**(6), 244–250.

Javor, K. (2013), *Diamond Jubilee: The 60th Anniversary of the Use of the 41 Inch Rod Antenna in Military EMI Testing*, In Compliance Magazine, Same Page Publishing, inc, Littleton, MA.
URL: *https://incompliancemag.com/article/diamond-jubilee-the-60th-anniversary-of-the-use-of-the-41-inch-rod-antenna-in-military-emi-testing/*

Kaminski, P. G. (1996), Affordability in the submarine force, Report, OFFICE OF THE UNDER SECRETARY OF DEFENSE ACQUISITION AND TECHNOLOGY.

Kazem, H. A. (2007), An improved method of passive input current waveshaping for single-phase rectifier, *in* '2007 Compatibility in Power Electronics', pp. 1–4.

Keiser, B. E. (1979), *Principles of electromagnetic compatibility*, 1979. 341 p., Artech House, Inc., Dedham, MA.

Kerr, C. I. V., Phaal, R. & Probert, D. R. (2008), 'Technology insertion in the defence industry: A primer', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **222**(8), 1009–1023.
URL: *https://journals.sagepub.com/doi/abs/10.1243/09544054JEM1080*

Kraus, J. & Fleisch, D. (1999), *Electromagnetics with applications*, McGraw-Hill.

Kraz, V. (1995), Near-field methods of locating emi sources, *in* 'RF EXPO WEST', pp. 392–397.

Leach, R. & Alexander, M. B. (1995), Electronic systems failures and anomalies attributed to electromagnetic interference, Report, NASA.

Mardiguian, M., Sweeney, D. L. & Swanberg, R. (2014), *Controlling radiated emissions by design*, Springer.

Mazzola, S. (2009), Mil-std-461: The basic military emc specification and it's evolution over the years, *in* '2009 IEEE Long Island Systems, Applications and Technology Conference', pp. 1–5.

MIL-STD-461A (1968), *MILITARY STANDARD: ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS REQUIREMENTS FOR EQUIPMENT, MIL-STD-461A*, Military Standard.

MIL-STD-461G (2015), *REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT, MIL-STD-461G*, DoD INTERFACE STANDARD.

NAVAIR (1975), *Electromagnetic Compatibility Design Guide for Avionics and Related Ground Support Equipment, AD115*, 3 edn.

Nguyen, C. (2019), Acma mandated emc standards, Report, Australian Communications and Media Authority.
URL: *https://www.acma.gov.au/-/media/Technical-Regulation-Development/Regulation/pdf/EMC_Standards_List.pdf?la=en*

Paul, C. R. (2006), *Introduction to electromagnetic compatibility*, John Wiley and Sons, Hoboken, NJ.

Redl, R. (1996), Power electronics and electromagnetic compatibility, *in* 'PESC Record. 27th Annual IEEE Power Electronics Specialists Conference', Vol. 1, pp. 15–21 vol.1.

Reed, J. H., Bernhard, J. T. & Park, J. (2012), 'Spectrum access technologies: The past, the present, and the future', *Proceedings of the IEEE* **100**(Special Centennial Issue), 1676–1684.

SAE (2003), *ARP958D Electromagnetic Interference Measurement Antennas Standard Calibration Method*, Society of Automotive Engineers,.
URL: *http://www.sae.org*

Schelkunoff, S. A. (1943), *Electromagnetic Waves*, Van Nostrand, Princeton, N.J.

Schelkunoff, S. A. & Friis, H. T. (1952), *Antennas: theory and practice*, Vol. 639, Wiley New York.

Schmid, M. E. & Crowe, D. G. (2001), 'Distributed computer architectures for combat systems', *Johns Hopkins APL technical digest* **22**(4), 488–497.

Schwartzbeck, D. (n.d.), *The EMI-Receiver according to CISPR 16-1-1*, Schwartzbeck Mess-Elektronik, Schonau.

Tektronix (2016), *Low-cost EMI Pre-compliance Testing Using a Spectrum Analyzer Application Note 37A-60141-1*, Vol. 37A-60141-1, Tektronix Inc.

Trujillo, E. (1995), Military requirements constrain cots utilization, *in* 'Proceedings of 14th Digital Avionics Systems Conference', pp. 112–117.

Videnka, R. & Svacina, J. (2009), Dealing with ambient disturbing signals at pre-compliance test sites, *in* '2009 19th International Conference Radioelektronika', pp. 271–274.

Williams, T. (2017), *EMC for product designers*, 5th edn, Newnes.

Wyatt, K. (2012), *The HF Current Probe: Theory and Application*, Interference Technology Magazine.
URL: *https://interferencetechnology.com/the-hf-current-probe-theory-and-application/*

Wyatt, K. (2016), Assembling a low cost emi troubleshooting kit – part 1 (radiated emissions), Report, ITEM Media.
URL: *https://interferencetechnology.com/assembling-low-cost-emi-troubleshooting-kit-part-1-radiated-emissions/*

Zombolas, C. (2010), The australian emc regulations, *in* '2010 Asia-Pacific International Symposium on Electromagnetic Compatibility', pp. 72–75.

Appendix A

Project Specification

ENG 4111/2 Research Project

Project Specification

For:	Luciano Colagiuri
Title:	Low-investment EMI pre-compliance for COTS technology insertion into submarine combat systems.
Major:	Electrical and Electronic Engineering.
Supervisors:	Dr. Andrew Maxwell
Enrolment:	ENG4111 - EXT S1, 2019 ENG4112 - EXT S2, 2019
Project Aim:	To determine potential compliance gaps between typical military electromagnetic compatibility (EMC) standards and those of typical commercial off the shelf (COTS) equipment items in order to ascertain risks of non-compliance of such equipment in a military environment. Further, to propose a reference set of low-cost and practical test protocols that may facilitate the identification of any specific compliance risks of such equipment.

Programme:

1. Research elements of EMC design in the military environment (such as in a submarine).
2. Research the motivation for COTS equipment insertion into such a military environment.
3. Determine the subset of electromagnetic interference (EMI) emissions limits and tests as applicable to (non-radio) equipment in such a military environment.
4. Research the suitability of COTS equipment in respect to EMC compliance in such a military environment.
5. Determine suitable, reduced-cost and practical EMI pre-compliance testing configurations.
6. Develop a proposed reference set of simplified, practical and relatively low cost radiated and conducted emissions test protocols which may be applied to COTS equipment with the aim of closing identified relevent military EMC compliance gaps.

As time and resources permit:

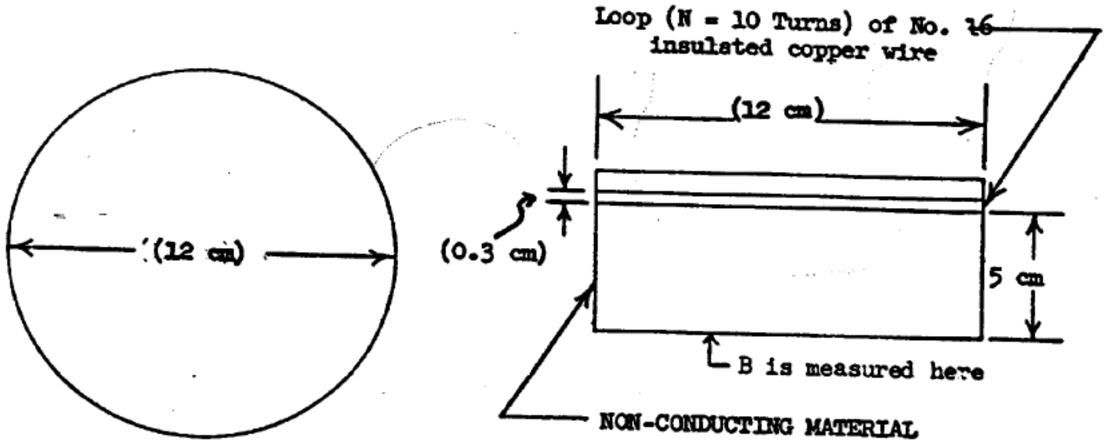
1. Experimental testing of these protocols (applying an upper frequency limit of 1GHz) to verify the viability of the proposed tests as a means of identifying EMC design risks.
2. Undertake experimental testing beyond 1GHz.
3. Compare experimental results with certified laboratory test results.

Appendix B

MIL-STD-461A Extracts

1. RS01 Loop Antenna Construction Details *Extracted from page 22 of MIL-STD-461A.*

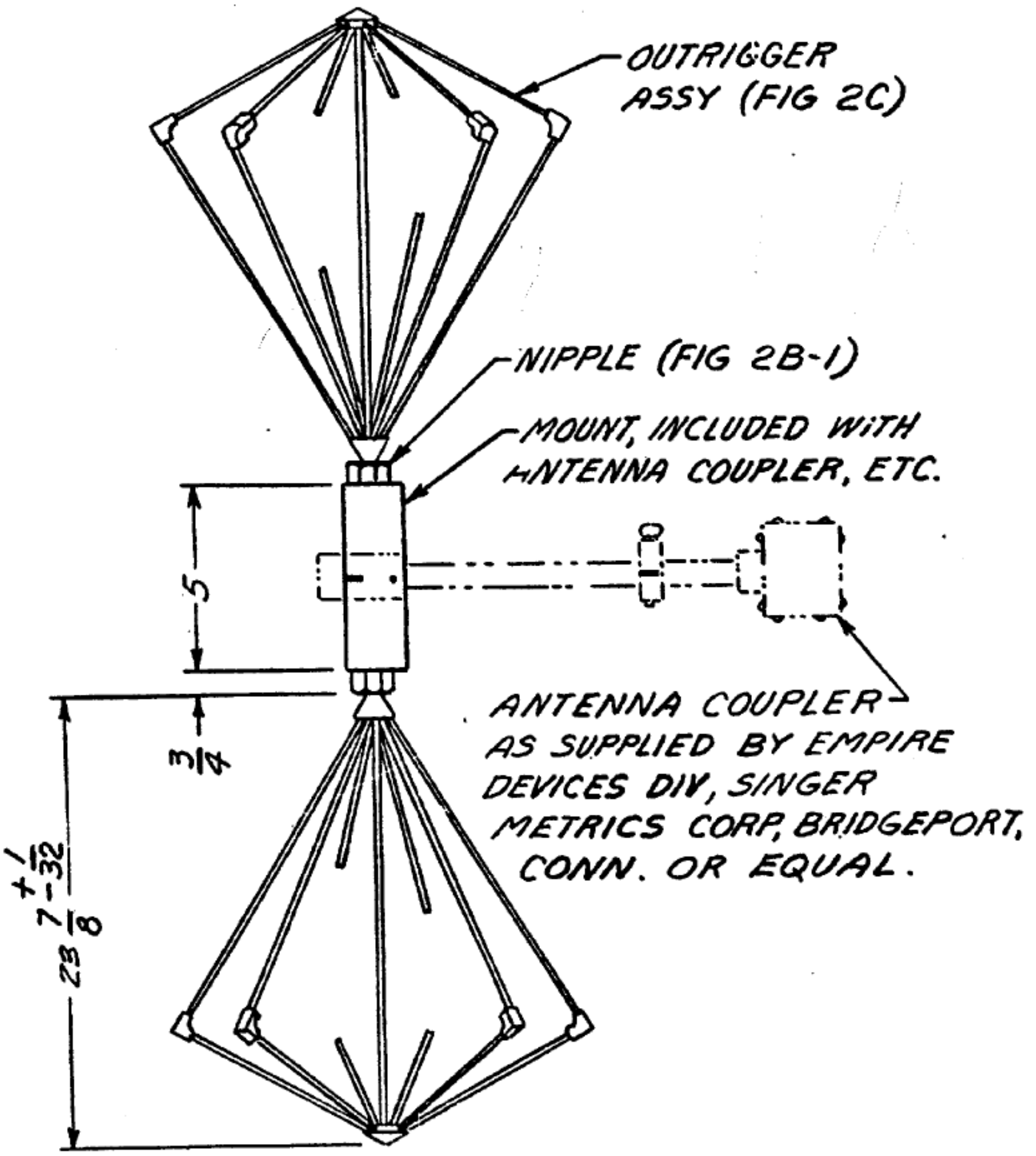
2. Biconical Antenna Construction Details *Extracted from pages 25 through 34 of MIL-STD-461A.*



NOTE 1: $B = 5 \times 10^{-5} \frac{\text{Tesla}}{\text{Amp}}$ at 5 cm from wire turns.

NOTE 2: LOOP SELF RESONANT FREQUENCY SHALL BE GREATER THAN 100 kHz.

Figure 1A- Loop used for radiating magnetic fields.



NOTE: DISCARD MOUNT SUPPLIED WITH ANT. COUPLER CU-893/URM-85, REPLACE WITH FIG. 2B-2. MOUNT INCLUDED WITH ANT. COUPLERS DM-105-T1 & DM-205-T1.

FIG 2B ANTENNA ASSEMBLY
(DRAWING ES-F-201286 SHEET 1)

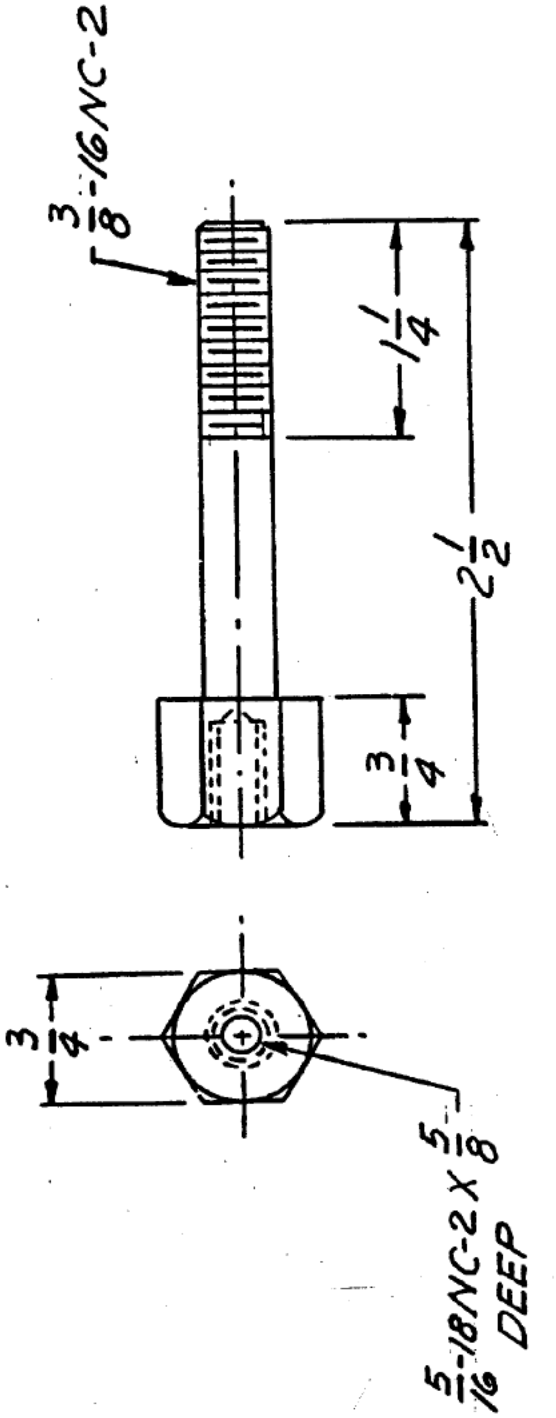


FIG 2B-1 BRASS NIPPLE

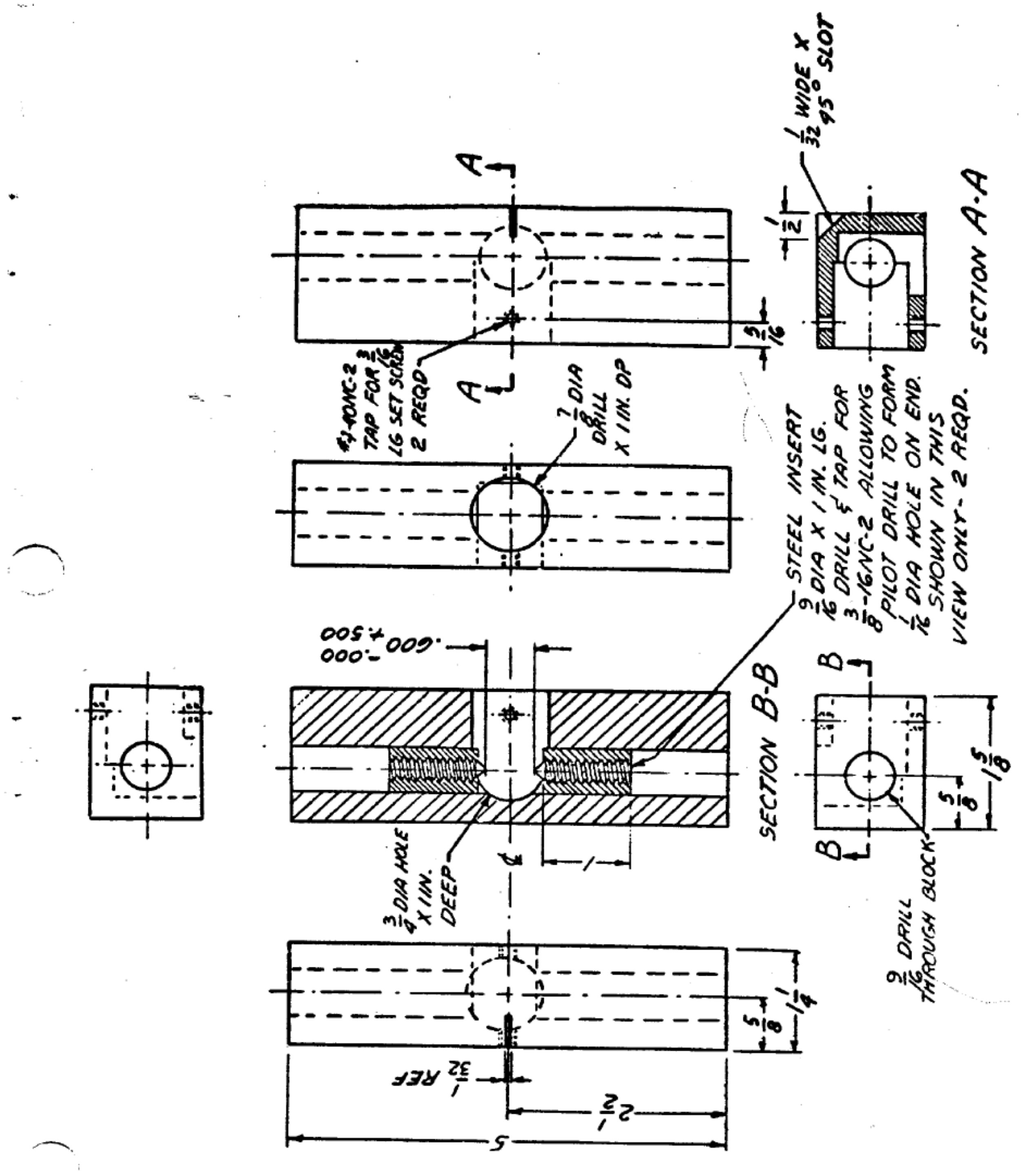


FIG 2B-2 PHENOLIC MOUNT

2430

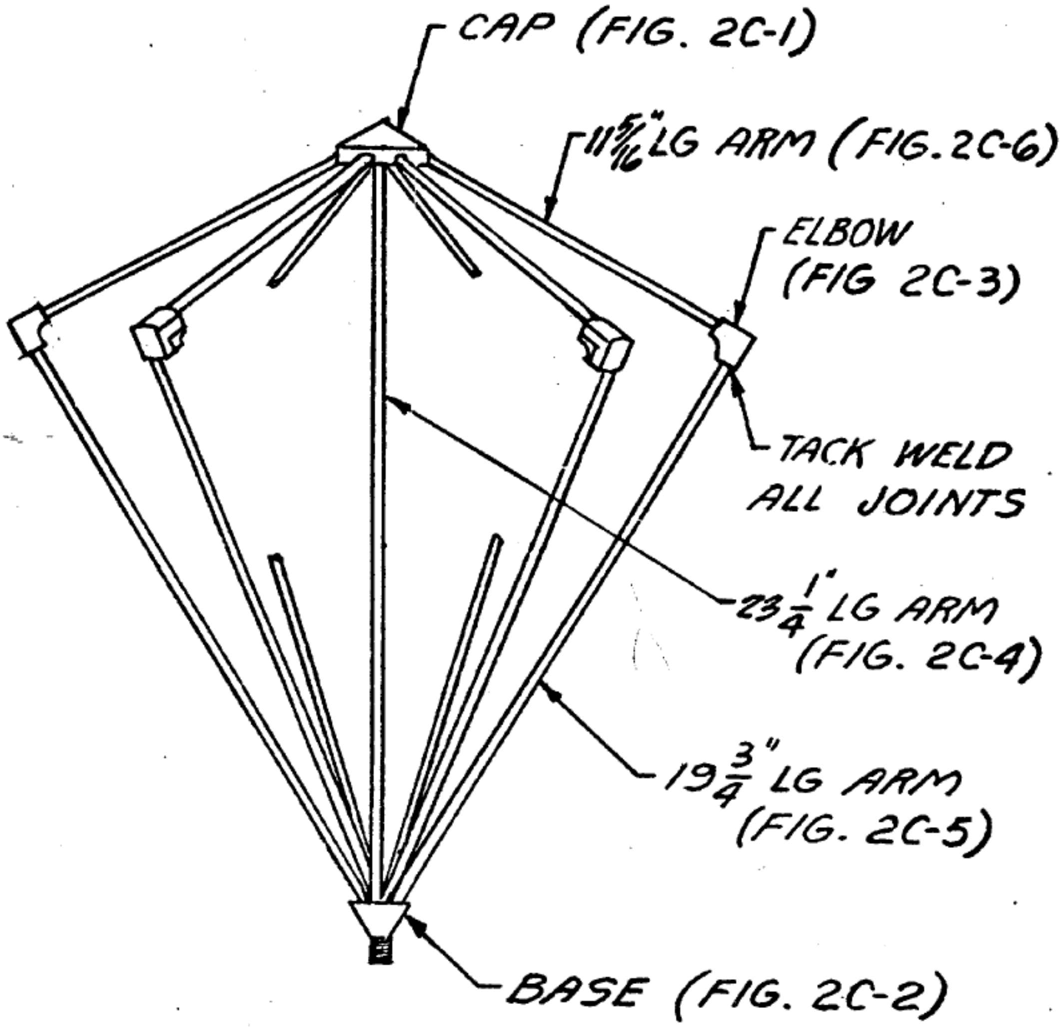


FIG 2C OUTRIGGER ASSEMBLY
2 REQD
(DRAWING ES-F-201286 SHEET 2)

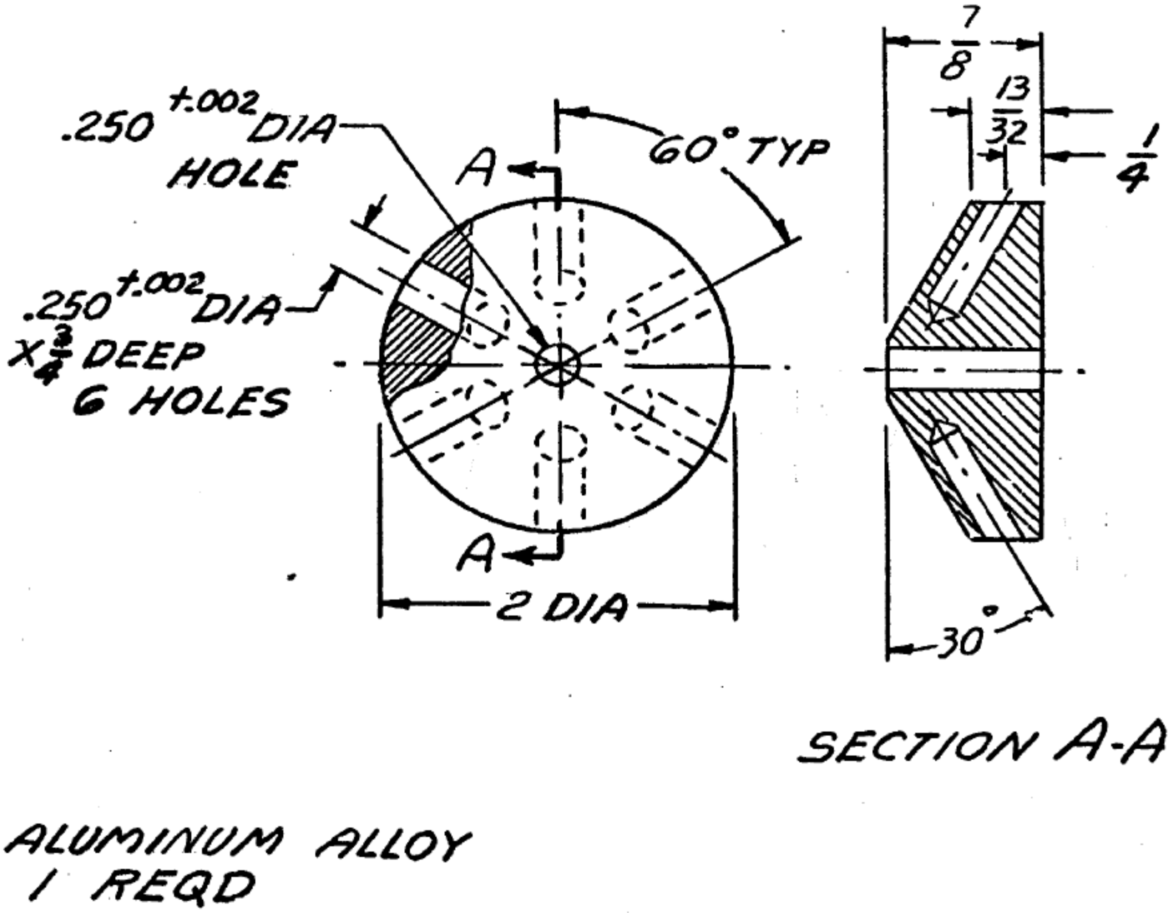
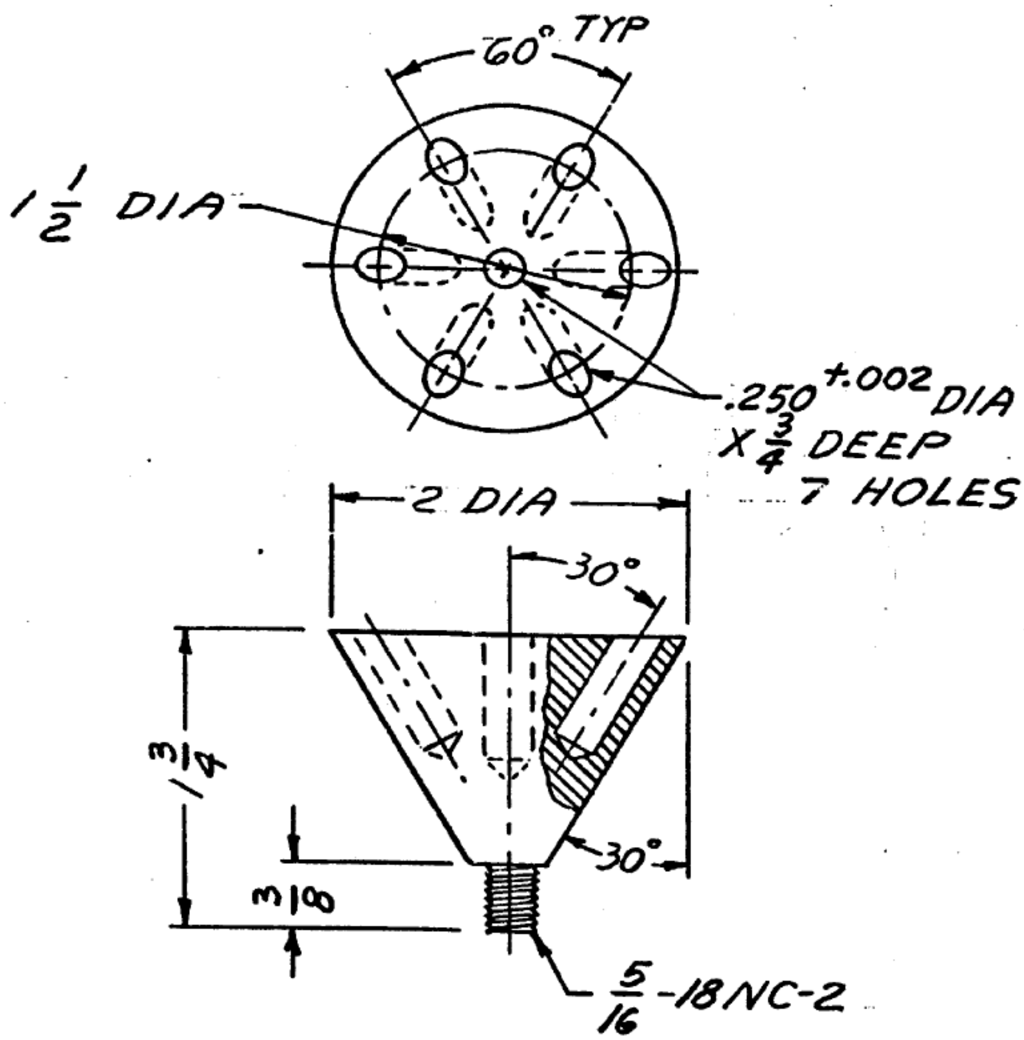


FIG 2C-1 CAP

2432



ALUMINUM ALLOY
1 REQD

FIG 2C-2 BASE

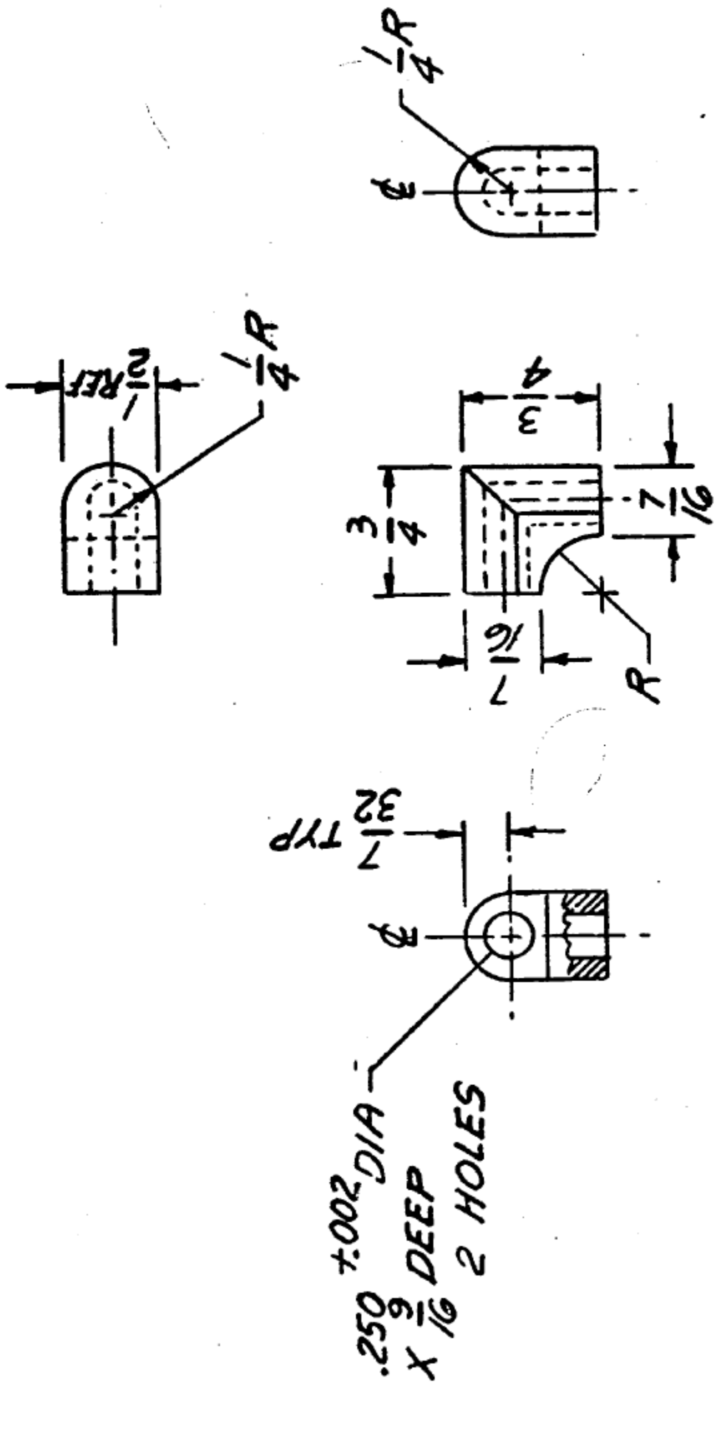


FIG 2C-3 ELBOW

ALUMINUM ALLOY
6 REQD

2436

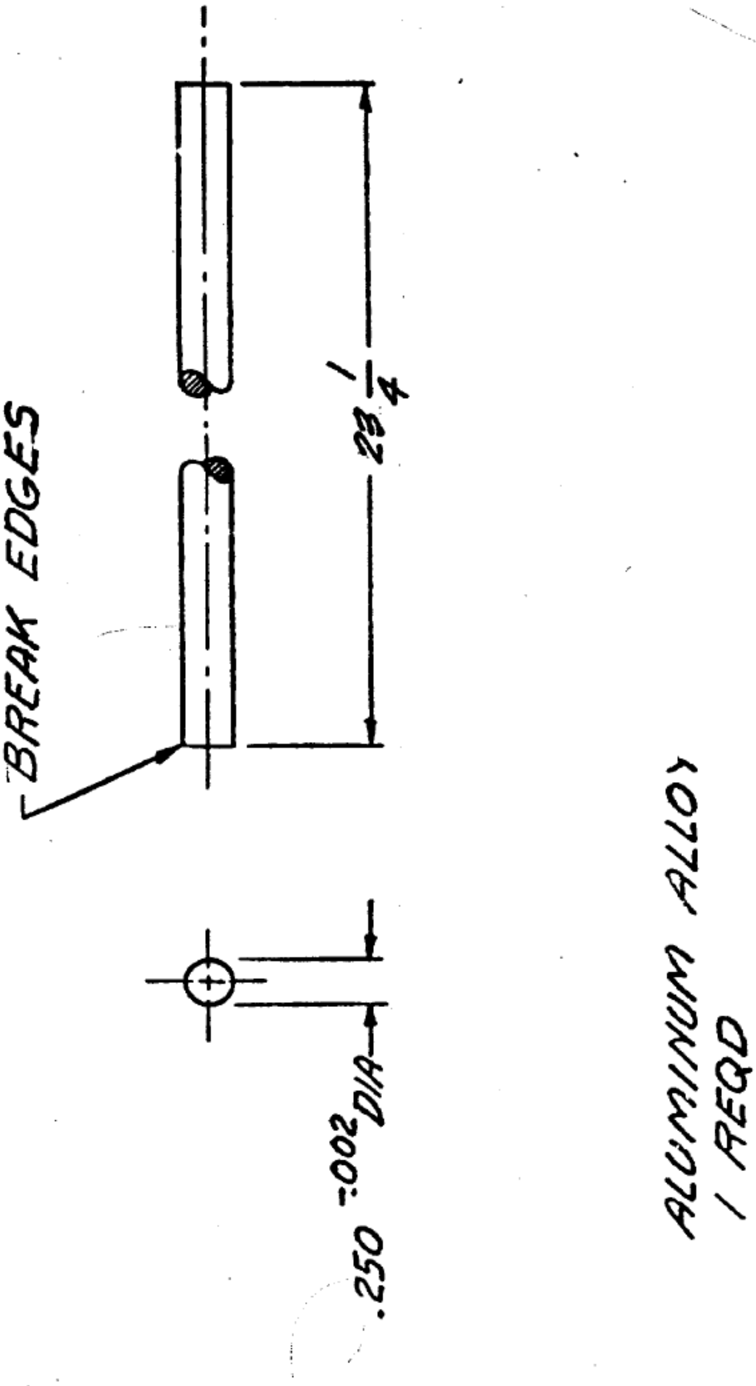


FIG 2C-4 ARM

2

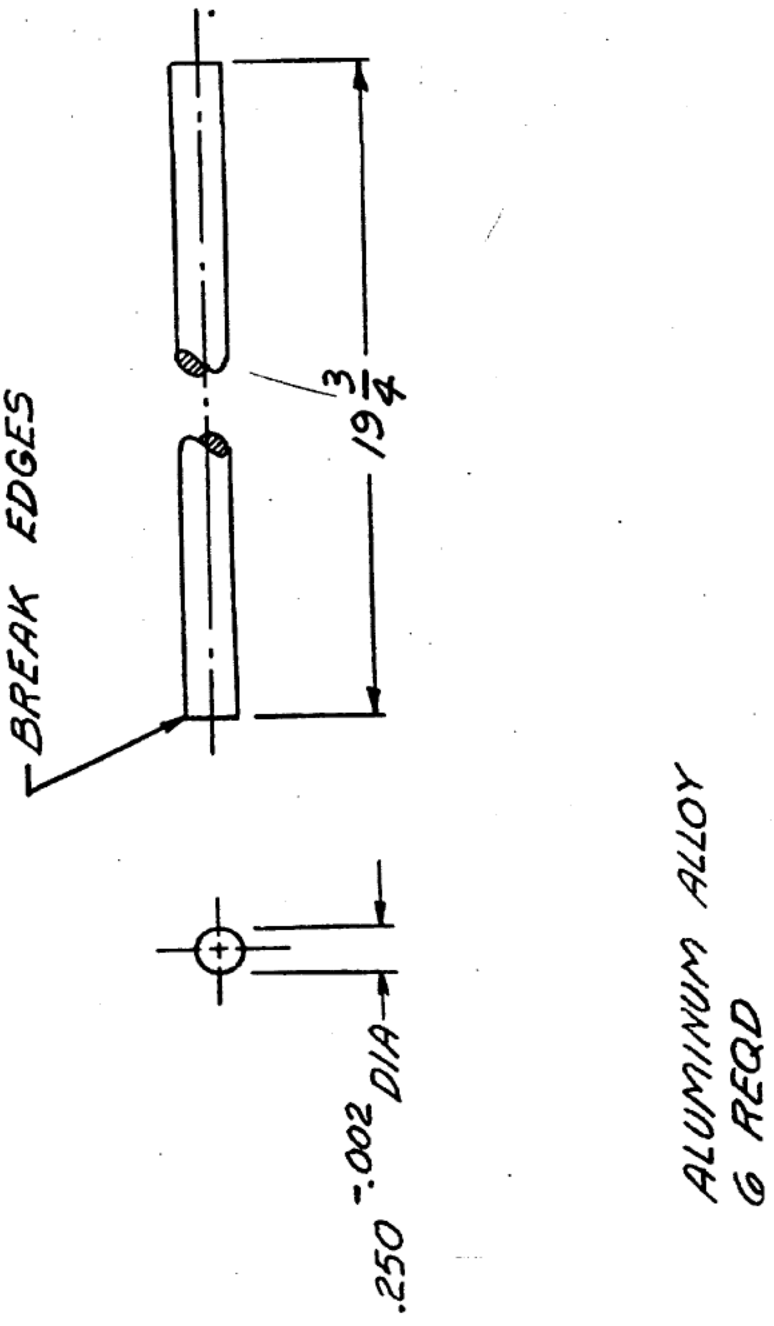
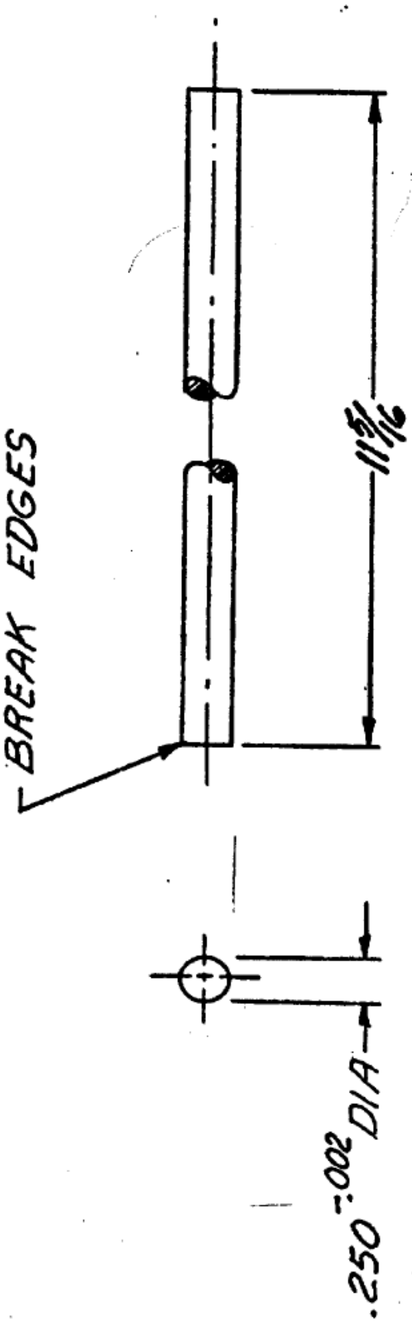


FIG 2C-5 ARM

2436
2863



ALUMINUM ALLOY
6 REQD

FIG 2C-6 ARM

Appendix C

Component Datasheets

1. YHDC SCT013-015-0-15-0-1V Split Core Current Transformer
2. Pomona Model 3430 Adapter - Binding Post to BNC Male
3. ThorLabs EF500 DC-Block
4. Minicircuits FTB-1-1+ Coaxial RF Transformer

Split core current transformer

YHDC®

Model：SCT013-015

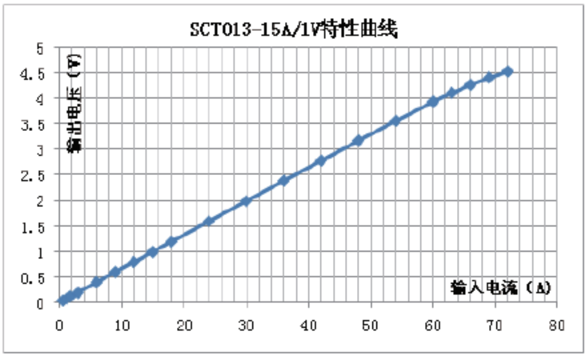
Characteristic:

Opening size 13mmx13mm, Compatible to foreign products, leading wire 1 metre, standardΦ3.5 three core plug output, current &voltage two types of output. (Patent No. ZL 2015 3 0060067.X）

Technical indicators:

Hanging installation,leading wire output
Fire resistance property:UL94-V0
Standard:GB1208-2006
Work temperature:-25℃～+70℃
Storage temperature:-30℃～+90℃
Work voltage:660V
Frequency range:50Hz-1KHz
Dielectric strength:3.5KV 50Hz 1min

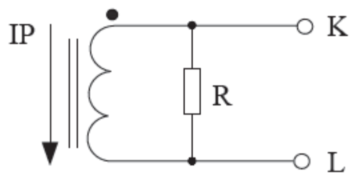
Characteristic curve in different load volt-ampere：



Electric parameter:

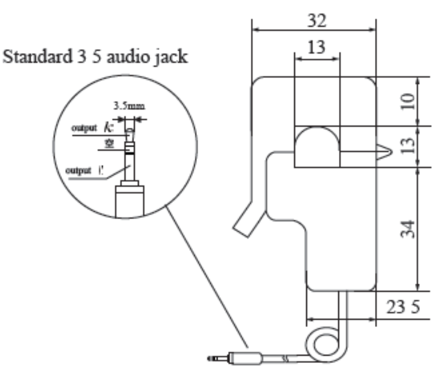
Rated input(rms)	15	A
Max.Input	40	A
Rated output	1	V
Turns ratio		
Accuracy	±1	%
Linearity	≤0.2	%
Phase error		
max:Sampling resistance		Ω
Weight	50	g

Wiring diagram:

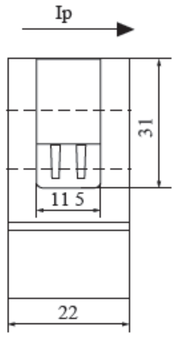


Built-in with sampling resistance
voltage output type

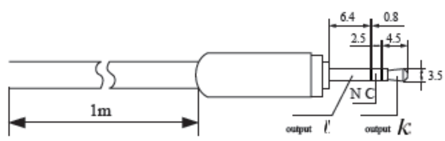
Outline size diagram(in mm):



Front view



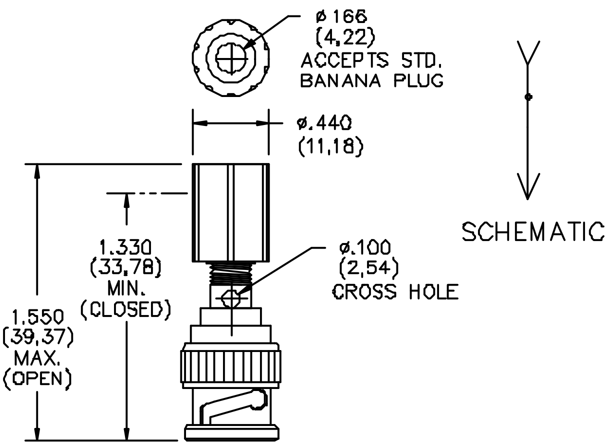
Side view



Standard three core jack schematic diagram

Pomona®

Model 3430
Adapter – Binding Post To BNC Male



FEATURES:

- Permits single banana plug to be used with equipment having a BNC female.

MATERIALS:

Upper Conn: Insulated Binding Post
Material: Binding Post Body – Brass per QQ-B-626, Allow 360, ½ Hard.
Finish: Nickel plated per QQ-N-290, Class 2, 200/300 microinches.
Insulation: Polycarbonate.
Color: See Ordering Information.
Lower Conn.: BNC Male
Finish: Body and fittings – Tarnish Resistant.
Nominal Impedance: 50 Ohms.

RATINGS:

Operating Temp.: +115º C. (+239º F.) Max.
Operating Voltage: Hand-held Testing: 30VAC/60VDC Max.
Hands free Testing in Controlled Voltage Environments: 500 VRMS Max.

ORDERING INFORMATION: Model 3430-*
* = Color, -0 Black, -2 Red
Ordering Example: 3430-2 Color is Red

All dimensions are in inches Tolerances (except noted): xx = ± 02" (,51 mm), xxx = ± 005" (,127 mm)
All specifications are to the latest revisions Specifications are subject to change without notice
Registered trademarks are the property of their respective companies Made in USA

DC Block Filter

EF500

Description

The EF500 DC Block Filter employs a modified 1st order Butterworth filter design. The design extends the low end of the 1 dB passband to 1 Hz in a BNC coaxial package. The EF500 is designed to terminate into DAQ, lab equipment, oscilloscopes, or any modern voltage signal transfer systems that have high impedance inputs. For $V_{transfer}$ systems, this architecture provides the highest signal-to-noise ratio capabilities.

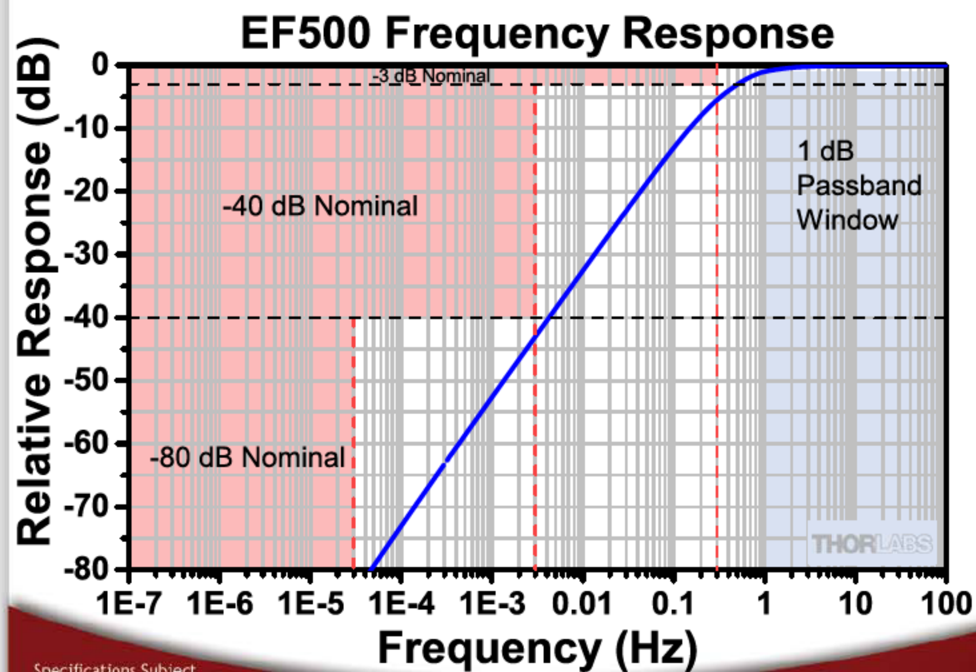
Specifications

EF500	
	Value[a]
Pulse Rise Time	>250 ps
Passband (1 dB Window)[b]	>1 Hz (Nominal)
3 dB Rejection	<0.3 Hz (Nominal)
40 dB Rejection	<3 mHz (Nominal)
80 dB Rejection	<30 µHz (Nominal)
Source Impedance (BNC Female)	50 Ω (Typical)
Load Impedance[c] (BNC Male)	≥100 kΩ
Input Voltage	±10 V (Max)
Storage Temperature	-20 to +70 °C

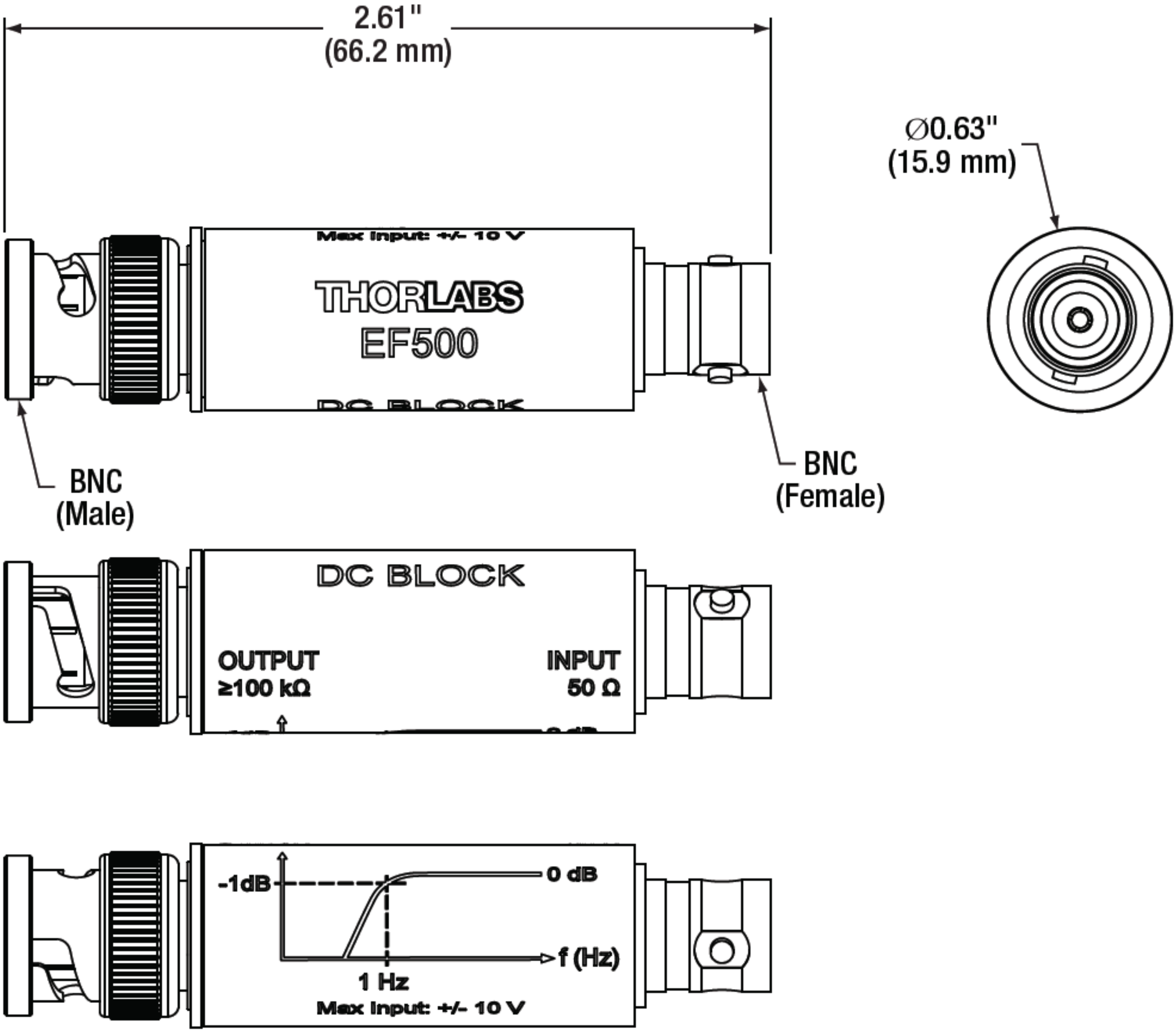
a. Values measured at 25 °C.
b. Performance measured to 600 MHz.
c. This filter can be operated with termination resistances below 1 kΩ, however, the passband will narrow at smaller termination resistances and the performance is not guaranteed.

Sample Response Data

Frequency (Hz)	Rel. Resp. (dB)
0.00003	-84.00
0.0003	-63.00
0.0027	-44.00
0.1	-12.40
0.3	-5.16
0.6	-2.29
0.8	-1.43
1	-0.95
1.5	-0.57
2	-0.35
3	-0.21
6	-0.07
10	-0.07
30	0.00
100	0.00



Drawings


2.61"
(66.2 mm)
Ø0.63"
(15.9 mm)
Max Input: +/- 10 V
THORLABS
EF500
BNC
(Male)
BNC
(Female)
DC BLOCK
OUTPUT
≥100 kΩ
INPUT
50 Ω
-1dB
0 dB
f (Hz)
1 Hz
Max Input: +/- 10 V

Coaxial

RF Transformer

FTB-1-1+

50Ω 0.2 to 500 MHz

CASE STYLE: H16-1

BNC Connectors	
Model	
FEMALE/FEMALE	FTB-1-1*A15(+)
MALE/FEMALE	FTB-1-1*C15+
BRACKET (OPTION "B")	

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 100°C
Storage Temperature	-55°C to 100°C
RF Power	250mW
DC Current	30mA

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections

	Marking
PRIMARY	BAL
SECONDARY	UNBAL

Features

- wideband, 0.2 to 500 MHz
- balanced to single-ended
- balanced port: isolated Female BNC

Applications

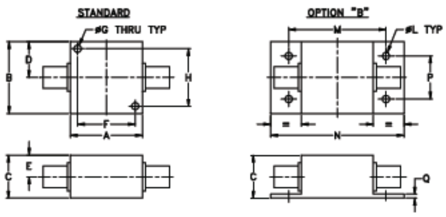
- DC Block

Transformer Electrical Specifications

Ω RATIO	FREQUENCY (MHz)	INSERTION LOSS*		
		3 dB MHz	2 dB MHz	1 dB MHz
1	0.2-500	0.2-500	0.5-300	1-100

* Insertion Loss is referenced to mid-band loss, 0.6 dB typ.

Outline Drawing



Outline Dimensions (inch / mm)

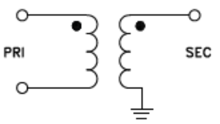
A	B	C	D	E	F	G	H
1.25	1.25	.81	.63	.41	1.000	.125	1.000
31.75	31.75	20.57	16.00	10.41	25.40	3.18	25.40

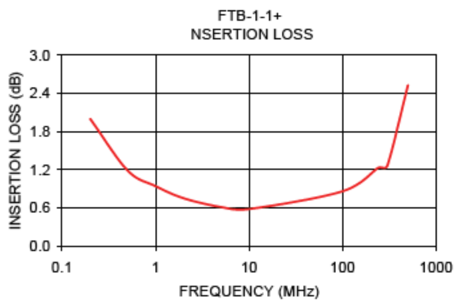
J	K	L	M	N	P	Q	wt
--	--	.125	1.688	2.19	.750	.06	grams
--	--	3.18	42.88	55.63	19.05	1.52	70.0

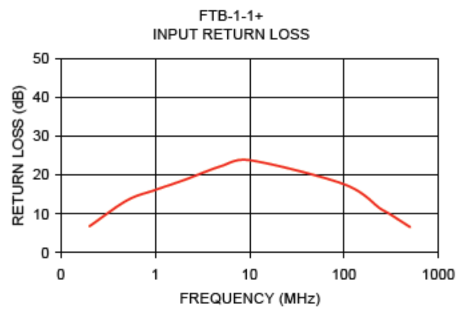
Typical Performance Data

FREQUENCY (MHz)	INSERTION LOSS (dB)	INPUT R. LOSS (dB)
0.20	2.00	6.79
0.50	1.19	13.47
1.00	0.94	16.19
2.00	0.75	18.70
5.00	0.61	22.34
10.00	0.58	23.84
100.00	0.86	17.64
241.48	1.23	11.38
300.00	1.26	10.05
500.00	2.53	6.59

Config. E







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Appendix D

Hazard Risk Assessment

Extracted from pages 59 and 60 of the Project Progress Report of ENG4111, Semester 1, 2019

6 Risk assessment

The following Risk Assessment process is based on the author's work-related EHS procedures and is based on his employer's EHS policies, which are aligned with both New South Wales and National legislation. Table 7 shows the Consequence descriptors and Table 8 shows the Liklihood descriptors to be use in accordance with the EHS risk management process.

Table 7. Hazard consequences

CONSEQUENCES			
Consequence Level	**Health and Safety**	**Environment**	**Regulatory**
Severe - 5	Fatality or sever permanently disabling injury.	Permanent damage to the natural environment.	Significant prosecution, including risk to company officers.
Major – 4	Minor permanent disability 9loos of finger or extended temporary impairment.	Long term environmental impairment of the ecosystem	Formal high level intervention (typically issuing of a Prohibition Notice). Risk of further interventions or penalties.
Moderate - 3	One or more Lost Time Injury Injuries. Overnight hospitalisation as an inpatient or Restricted Duty case	Medium term environmental impairment of the ecosystem	Formal intervention (typically issuing of an Improvement Notice). Unlikely to escalate if complied with.
Minor – 2	Temporary or reversible injury requiring medical treatment to one or more people. Classified as a Medically Treated Injury.	Short term environmental impairment of the ecosystem	Risk of punitive action is unlikely with any intervention limited to and inspectors visit and report.
Insignificant - 1	Minor injury requiring first aid	Minor environmental impairment of the ecosystem	No risk of punitive actions, and any intervention limited to observation.

Table 8. Hazard likelihood

LIKELIHOODS		
Criteria	**Description**	**Frequency**
Almost certain	Expected to happen	Occurs once a week
Likely	May easily happen	Occurs once a month
Possible	May happen	Occurs once every year
Unlikely	May happen sometimes	Occurs once every 10 years
Rare	May happen in extreme circumstances	Occurs once every 100 years

This project will almost certainly not include any activities undertaken at the Employer's premises. To the same extent, no activities as planned to be undertaken at the University of Southern Queensland, other than the normal presentation and workshopping activities as required under ENG4903 during Engineering Week and the Project Conference.

Determination of the level of risk was made by using the risk matrix in Table 9, the outcome of which is listed without the application of any controls or Risk Mitigation Measures in Table 10.

A further determination of the level of risk shall be made by using the risk matrix in Table 9, based on appropriate

Risk Mitigation Measures, the outcome of which is also listed in Table 10.

Table 9. EHS Risk Level Matrix

EHS RISK LEVEL						
Likelihood	Almost Certain	Medium	Medium	High	High	Extreme
	Likely	Medium	Medium	Medium	High	Extreme
	Possible	Low	Medium	Medium	High	High
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	Medium	Medium
		Insignificant	Minor	Moderate	Major	Severe
Consequences						

Table 10. Hazard Risk Assessment for Research Project

Risk/Hazard Description	**Risk Mitigation Measures**	**Risk Score before measures**	**Risk Score after measures**
Electric Shock from Mains connection of test configuration	Use of insulated cables and terminals. Every piece of equipment is earthed. Peer reviewed wiring prior to energising. No open chassis. DUTs powered remotely and not to be touched during testing. All DUTs have IEC mains inlets and have electrical safety certifications.	**High**	**Low**
Exposure to elevated radiated radio frequency field strengths to be beyond that considered safe for human exposure and the requirement to adhere to ARPANSA specified limits. RF signal generators used are not high power devices.	A comparison of the maximum allowable electric and magnetic field strengths set by ARPANSA (Standard 2002) and the limits expected during pre-compliance experiments should be undertaken. In the specific case of the radiating sample of Section 3.3.2.4, caution should be taken to start with very low signal strength, working up to a measurable level, staying well under the ARPANSA limits.	**High**	**Low**
Ill effects from breathing soldering fumes.	Minimal soldering required. PPE worn and fumes exhausted away from bench.	**Medium**	**Low**
Radiated interference generated during calibration and testing activities. It is expected that some calibration signals may be of a higher level that the AS/NZS limits for Class B residential equipment.	It will be planned that all such testing will only take place after midnight to 5am to limit the possibility of nuisance emissions. If possible, monitor and limit calibration transmission levels to meet AS/NZS-CISPR-32.	**Medium**	**Low**