



Design of a shielded turntable with reduced radiated emissions for EMC and antenna testing applications.

by

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Submitted in partial fulfilment of the requirements for the degree: Master of Satellite Systems and Applications in the Faculty of Engineering at the Cape Peninsula University of Technology

Bellville

February 2026

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Dr. P.G. Wiid, my supervisor, for his technical guidance, support, and insight throughout this research.

Special thanks to EMSS Antennas, my employer, for providing access to facilities, equipment, and design documentation that were instrumental in the development and testing of the antenna test turntable.

I also appreciate the assistance of the SRAO RFI team for facilitating compliance-level EMC testing and access to the reverberation chamber.

Lastly, I am grateful to my colleagues, friends, and family for their encouragement and support throughout this journey.

ABSTRACT

Electromagnetic compatibility (EMC) testing is critical for ensuring reliable operation of electronic systems in increasingly complex electromagnetic environments. At the Cape Peninsula University of Technology (CPUT), the need for consistent and repeatable EMC and antenna measurements led to the development of a shielded, automated antenna test turntable (ATT). This research details the design, implementation, and validation of a low-emission, portable turntable platform for use in shielded chambers and open-area test sites. The project followed a structured engineering design methodology, beginning with a comprehensive literature review on EMC principles, EMI sources, coupling mechanisms, and applicable standards such as CISPR 32, IEC 61000, and MIL-STD-461. The ATT was engineered to rotate equipment under test (EUT) through 360° with high positional accuracy ($\pm 1^\circ$), while minimizing electromagnetic interference using shielded enclosures, filtered connectors, and fibre-optic communication.

Subsystems—including a linear power supply, stepper motor with driver, and a microcontroller-based control interface—were housed in dedicated RFI-shielded cavities. Functional testing confirmed reliable rotation under a 25 kg load at speeds up to 3 rpm, precise angular control within $\pm 1^\circ$, and robust serial communication over 10 m fibre-optic links.

Pre-compliance EMC testing using near-field probing and common-mode current measurements demonstrated emission attenuation of up to 30 dB compared to an unshielded configuration. Common-mode coupling remained below 14 dB μ A, supporting the platform's low-noise design. Compliance-level radiated emissions testing confirmed adherence to CISPR 32 Class B limits, with measured peak emissions at least 15 dB below the limit across 30 MHz–300 MHz and an average margin of 30 dB below the limit from 0.3–6 GHz. No pulsed emissions were detected, validating the system's suitability for sensitive EMC and antenna testing environments.

A cost saving of approximately 80% was achieved compared to commercial EMC turntables. This research delivers a cost-effective, low-noise solution for automated EMC testing and lays the foundation for future enhancements such as closed-loop control, advanced shielding, and integrated sensor feedback.

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LIST OF ABBREVIATIONS

ACW	Anticlockwise	kHz	Kilohertz
ADC	Analogue to digital converter	LCD	Liquid crystal display
AI	Analogue interface	LED	Light emitting diode
ASCII	American Standard Code for Information Interchange	LISN	Line impedance stabilization network
ATT	Antenna test turntable	LUF	Lowest usable frequency
CAD	Computer-aided design	MCU	Microcontroller
CCM	Common-mode capacitor	MDF	Medium-density fibreboard
CENELEC	European Committee for Electrotechnical Standardization	MHz	Megahertz
CISPR	Committee on Special International Committee on Radio Interference	MIL-DTL	Military detail specification
CMC	Common mode current	MIL-STD	United states military standard
CNC	Computer numerical control	MK	MeerKAT radio telescope
COTS	Commercially off the shelf	NF	Near field
CPU	Central processing unit	OATS	Open area test site
CW	Clockwise	ODC	Outdoor connector (fibre optic type)
DAC	Digital to analogue converter	PCB	Printed circuit board
DC	Direct current	PCBA	Printed circuit board assembly
DPX	Digital phosphor (spectrum analyser display mode)	PEEK	Polyetheretherketone (high-performance engineering plastic)
EEPROM	Electrically erasable programmable read-only memory	PF	Power factor
EM	Electromagnetic	PM	Project management
EMC	Electromagnetic compatibility	PSRR	Power supply rejection ratio
EMI	Electromagnetic interference	PSU	Power supply unit
EMSS	EMSS Antennas	PVC	Polyvinyl chloride
EN	European Norm (European standard)	PWM	Pulse width modulation
ETS	Electromagnetic Test Systems	RAM	Radio absorbing material
EUT	Equipment under test	RBW	Resolution bandwidth
FPGA	Field programmable gate array	RCMU	Receiver control and monitoring unit
GHz	Gigahertz	RF	Radio frequency
GPIO	General purpose interface bus	RTSA	Real-time spectrum analyser
GUI	Graphical user interface	SKA	Square Kilometre Array telescope
HFBR	High-Frequency Broadcom Receiver (Avago fibre optic series)	SMA	Sub miniature version A (RF connector type)
IC	Integrated circuit	SPI	Serial peripheral interface
IEC	International Electrotechnical Commission	TIP36C	Power transistor
IEEE	Institute of Electrical and Electronics Engineers	TMBF	Time mean between failures
ISP	In-system programming	UART	Universal asynchronous receiver/transmitter
I ² C	Inter-integrated circuit	UC2836	Voltage regulator controller
		UHF	Ultra-high frequency
		USB	Universal serial bus
		VCC	Voltage common collector
		VDC	Voltage direct current
		ZAR	South African Rand (currency)

CHAPTER 1 INTRODUCTION

1.1 MOTIVATION

At CPUT, the department of electronic, electrical and computer engineering regularly aim to perform experimental tests on equipment developed by the department. More specifically, F'SATI at CPUT regularly needs to perform tests on antennas and satellite subsystems to ensure electromagnetic compatibility (EMC).

To date, the department cannot complete comprehensive on campus EMC tests as stipulated by international EMC directives and standards. The disadvantage of the methods currently used to test equipment is that it is mostly prone to human error. It's a manual process, and the university are unable to achieve consistency in test methods and setups. The use of automated equipment as far as possible will significantly increase the effectiveness and consistency of test results. CPUT is currently in the process of establishing a more robust and adequate electromagnetic test facility and has decided the most cost-effective way to achieve completion of a test facility is by students assisting with the research and development of critical test equipment needed. One essential piece of equipment required is an automated turntable platform to be used in a screened environment for EMC and antenna testing. The use of an automated turntable platform will significantly improve the repeatability of tests to be performed. However, the automated turntable control system should not interfere with measurements. Commercial off-the-shelf turntables are typically expensive, do not provide sufficiently low emissions for strict EMC and antenna measurements, and offer limited options for customisation. Therefore, it is required to investigate, design, and manufacture a prototype automated (remote controlled) portable turntable platform with reduced emissions to be used for EMC and antenna testing. A portable unit can be used in any screened chamber or at an Open Area Test site.

1.2 RESEARCH PROBLEM

When performing comprehensive EMC and antenna measurements, test standards stipulate that the device under test needs to be rotated and measurements repeated at various rotational angles. There is a requirement to develop a prototype to automatically rotate devices under test when performing EMC and antenna measurements while not interfering with the measurements being done.

1.3 RESEARCH OBJECTIVES

The objective of this study is to complete a comprehensive literature study showing a complete understanding of the basic EMC and antenna testing theory, EMC and antenna testing methods, and design techniques to reduce electromagnetic (EM) / radio frequency (RF) emissions. These design techniques will then be implemented in the design, manufacture and testing of a prototype portable turntable for EMC and antenna testing. The prototype will provide position feedback during testing and will be a shielded design with low/no EM/RF emissions.

1.4 RESEARCH QUESTIONS

The following list of research questions was asked, the outcomes was unknown and was investigated.

1. Why do we need a turntable for EMC and antenna testing?
2. What EMC and antenna testing standards apply to the research?
3. What are the requirements of a turntable used in EMC and antenna testing?
4. What electronic design techniques can be used for reduced radiated emissions?
5. What practical and cost effective EM shielding methods can be used?
6. What hardware and materials are best to use when designing for reduced radiated emissions?

1.5 DELIMITATION OF THE RESEARCH

The research will focus on the electronic design of a turntable control system with reduced emissions. The frequency range of reduced emissions is between 50 - 1000 MHz, and the limits applicable are mandated by test standards. Only design techniques and methods for reduced emissions will be investigated and implemented to construct a prototype turntable. The subsystems will be pre-compliance tested but not certified. It is assumed that access to the CPUT laboratories and other testing facilities will be available through consultation with my supervisor.

1.6 OUTLINE OF DISSERTATION

The dissertation employed an engineering design methodology (Khandani, 2005) , a systematic approach to problem-solving and developing solutions to engineering challenges. It involves a succession of steps to identify, define, analyse, and resolve problems or achieve objectives in an organised and efficient manner. The sections below briefly describe the various steps in the process.

1.6.1 PROBLEM DEFINITION PHASE

The first step is the problem definition phase, where the problem is clearly defined and the engineering problem is clearly articulated. This generally includes identifying the stakeholders, context and constraints and defining the research objectives and criteria for success. This phase is detailed in section 1.1 to 1.5.

1.6.2 LITERATURE STUDY PHASE

A literature review examined all sources of information applicable to the research, this included relevant identifying theoretical concepts , practical and commercially available solutions, and test methods. It identified existing technologies and solutions and where these solutions fall short, and laid a foundation for design choices.

1.6.3 REQUIREMENTS DEFINITION PHASE

In the requirements definition phase, the requirements of the ATT were identified. This included functional and EMC performance requirements, dimensions and weight requirements and cost. In this phase the methods used to confirm these requirements are defined.

1.6.4 CONCEPTUAL DESIGN PHASE

The conceptual design phase involved brainstorming ideas and potential solutions on how the requirements can be met. The conceptual design establishes the major system characteristics that is required to meet the requirements. The concept is then evaluated against the requirements before proceeding with detailed design.

1.6.5 DETAILED DESIGN AND PROTOTYPE DEVELOPMENT

In this phase a detailed design based on the selected concept is developed. This includes specifying detailed system components, materials, dimensions, and manufacturing processes. Part of the process is to analyse the selection of components and perform simulations where applicable. In this phase, prototype development also happens. This includes physical prototypes of the subsystems of the design. Prototyping allows one to verify functionality, assess performance, and identify potential issues early in the process before system integration.

1.6.6 TESTING, EVALUATION AND ITERATION

During this stage, the complete prototype and subsystems undergoes thorough testing and assessment. This process includes functional, EMC, and usability tests. The outcomes of these tests guide necessary refinements or iterations of the design.

1.6.7 CONCLUSIONS AND RECOMMENDATIONS

After testing and iteration, the system's performance is evaluated with test data, and feedback is provided for improvements or future iterations.

CHAPTER 2 LITERATURE STUDY

This chapter provides the literature reviewed as part of this research.

2.1 WHAT IS ELECTROMAGNETIC COMPATIBILITY

Electromagnetic interference (EMI) resembles environmental pollution like chemical contamination (Williams and Armstrong, 2000). While pollutants harm the physical environment, electromagnetic pollution impacts the spectrum vital for modern tech. In modern days society depends heavily on electronic and wireless systems, protecting this environment is essential for safety, reliability, and economic stability as many industries are dependent on the systems. Electromagnetic compatibility (EMC) is the engineering field focused on ensuring electrical and electronic devices work as intended within their electromagnetic environments . According to the International Electrotechnical Commission, EMC is defined as “the ability of equipment or a system to function satisfactorily in its electromagnetic environment without causing unacceptable electromagnetic disturbances to other equipment and systems in that environment” (Williams and Armstrong, 2000). (Morgan, 2007) describes EMC as the capacity of equipment and systems to function as intended within its electromagnetic environment without degradation, malfunction, or interference with other systems. Each EMC issue involves three elements: (1) an energy source, (2) a coupling path, and (3) a vulnerable receiver. This relationship, shown in Figure 2.1 is key to EMC analysis. Interference happens when the coupling allows energy from the source to reach the victim, causing malfunction. Solving EMC problems typically involves identifying and mitigating at least two of these elements (Introduction to EMC, 2018). EMI can reach the victim through conducted or radiated coupling paths.

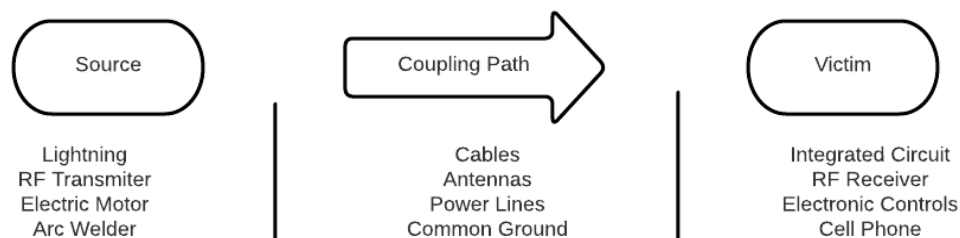


Figure 2.1: EMC elements (adapted form LearnEMC, 2018).

2.2 UNDERSTANDING ELECTROMAGNETIC RADIATION

The next section explores EMI sources and coupling pathways affecting sensitive equipment, forming the basis for EMC management and design. As covered by (Siglent Technologies,

2017) EM radiation in electronic systems is primarily caused by current flow or voltage variations along conductors, including PCB traces, component leads, discrete wires, connectors, and metallic enclosures. EM radiation consists of two orthogonal components: the electric field (E-field) and the magnetic field (H-field), which propagate together as an electromagnetic wave as shown in Figure 2.2.

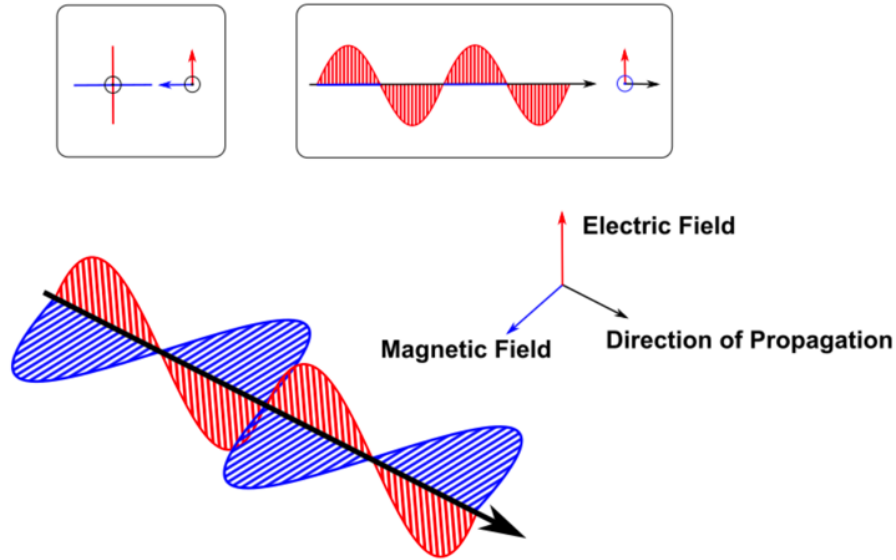


Figure 2.2: Electromagnetic wave propagation (from Siglent, 2017).

Magnetic fields are generated exclusively by moving charges (currents) and are particularly prominent near signal and power-carrying conductors, such as PCB traces, ribbon cables, and component leads. These magnetic fields form concentric loops around the conductor, a pattern that can be described by Ampère's law and visualized using the right-hand rule, where the direction of the current determines the orientation of the magnetic field lines.

For a circular path centred on the wire Ampere Law simplifies to:

$$B = \frac{\mu_0 I}{2\pi r} \quad (2.1)$$

Where:

- B is the magnetic flux density at a distance r from the wire
- I is the current in the wire
- μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m)
- r is the radial distance from the wire

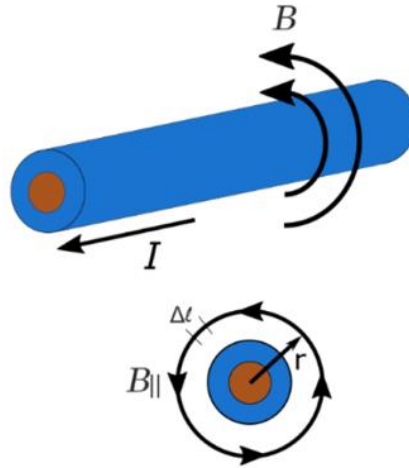


Figure 2.3: Magnetic field produced by current (from Siglent, 2017).

Electric fields, on the other hand, can be created by both moving and static charges, and tend to dominate in regions near conductive surfaces such as metal enclosures, heatsinks, display edges, or slots, where charges can accumulate. Near field probes are commonly used to measure both E- and H-fields close to the source, which allows engineers to locally identify EMI sources on a circuit board or cable. In the far-field region, which is typically several wavelengths away from the source, the electric field often dominates, and measurements are more susceptible to environmental interference from radio stations, WIFI networks, or other unintended RF sources (Siglent Technologies, 2017)(Ott, 2009).

2.3 EMI SOURCES AND COUPLING MECHANISMS

Understanding EMI involves identifying its sources “natural or man-made” and the coupling paths, which can be conductive or radiative (Ott, 2009). This section elaborates on EMI sources and coupling mechanisms.

2.3.1 NATURAL SOURCES

There are natural phenomena such as lightning, electrostatic discharge (ESD), and solar activity that leads to unpredictable electromagnetic interference. Lightning can produce powerful EM fields that can cause surges on power and communication systems. Additionally solar flares and geomagnetic storms can disrupt long-distance communication, satellite operations, and navigation systems by affecting radio wave propagation. (Paul, 2006). While these sources cannot be completely eradicated, their effects can be mitigated.

2.3.2 MAN-MADE SOURCES

According to (Williams, 2007a). man-made EMI originates from both deliberate and accidental electromagnetic emissions generated by electrical and electronic devices. Intentional radiators, like radio transmitters, radar systems, and mobile communication devices are specifically

designed to emit electromagnetic energy for communication or sensing. If not regulated properly they can potentially interfere with other nearby systems. Unintentional radiators include all other devices that emit electromagnetic energy as a by-product of their operation. These include switching power supplies, electric motors, relays, microcontrollers, pulse-width-modulated motor drives, etc. As switching speeds in modern electronics continue to increase, therefore too does the likelihood of unintentional EMI generation.

2.3.3 COUPLING MECHANISMS

Electromagnetic energy couples from source to victim via mechanisms like conducted, radiated, and inductive or capacitive coupling, which vary with frequency, circuit layout, grounding, and shielding. (Ott, 2009; Introduction to EMC, 2018).

2.3.3.1 CONDUCTED COUPLING

Conducted coupling involves unwanted currents or voltages transferred along shared paths like cables or ground connections, generally at frequencies below 30 MHz where the disturbance wavelength is large. Conducted EMI is categorized as either common-mode (currents flowing the same way in multiple conductors) or differential-mode (currents flowing oppositely). Mitigation methods include line filters, common-mode chokes, and capacitive bypassing to reduce high-frequency noise (Ott, 2009; Introduction to EMC, 2018). The effects can be mitigated by careful PCB layout, cable segregation, and differential signalling techniques. CISPR 16-1-2 and IEC 61000-2-1 define methods for measuring conducted disturbances up to 30 MHz (IEC, 1990; CISPR, 2014).

2.3.3.2 RADIATED COUPLING

When a source and victim interact through electromagnetic fields in free space it is defined as radiated coupling. This generally occurs at frequencies above 30 MHz, cables, traces, and small loops can act as antennas, emitting or receiving energy. The coupling's strength depends on geometry, distance, and shielding effectiveness. Some mitigation measures include good enclosure design, grounding, and minimal loop areas in PCBAs (Ott, 2009; Introduction to EMC, 2018).

2.3.3.3 CAPACITIVE AND INDUCTIVE COUPLING

Capacitive and inductive coupling are near-field mechanisms occurring at short distances. Capacitive coupling involves electric field interactions between conductors separated by a dielectric, creating displacement currents proportional to voltage change. Inductive coupling is caused by magnetic fields, where changing current in one conductor induces a voltage in an

adjacent loop per Faraday's Law. These mechanisms dominate in dense circuits or wiring harnesses. Proper cable segregation, twisting pairs, and shielding help reduce coupling (Paul, 2006).

2.4 EMC STANDARDS

With advances in technology, protecting the electromagnetic spectrum is increasingly essential, especially for communication, navigation, and control systems,. There is an increase in EMI risks with the increase in complexity and density of electronic device, thus regulations are required to ensure electromagnetic compatibility. Due to the need for regulations various organizations have developed EMC standards and directives that govern the design, testing, and certification of electronic equipment. These standards assist to ensure devices function properly within their electromagnetic environments and do not interfere with other systems (Williams, 2007; European Commission, 2014).

2.4.1 EVOLUTION AND PURPOSE OF EMC STANDARDS

EMC standards have developed alongside advancements in radio and electronic technology. In the 1930s, early interference problems, mainly affecting broadcast radio, resulted in the formation of the Comité International Spécial des Perturbations Radioélectriques (CISPR) under the IEC, aimed at coordinating efforts against radio disturbances. As electronics became widespread across various industries in the latter 20th century, unregulated emissions began to pose risks not only to communication systems but also to critical infrastructure like aviation and medical equipment. This led to the creation of harmonized EMC standards and directives designed to safeguard the electromagnetic spectrum, ensure interoperability, and support fair trade through certification based on compliance. (EU, 2014).

Today, EMC standards serve several essential purposes:

- To limit electromagnetic emissions produced by equipment.
- To define immunity requirements that ensure functional reliability in the presence of interference.
- To establish uniform test procedures for global comparability.
- To support legal compliance and market access across regions.

In the European Union, these standards are formalized through the electromagnetic compatibility directive. This directive requires all electronic products to meet specific emission and immunity criteria prior to being marketed (EU, 2014).

2.4.2 IEC 61000 SERIES

The IEC 61000 series underpins EMC regulations in the EU and numerous other regions. It establishes emission limits and immunity testing procedures, offering a complete framework for assessing the electromagnetic compatibility of electrical and electronic devices. The standard is divided into multiple parts addressing general, measurement, and specific test requirements.

For this research, the following parts are of particular relevance:

- **IEC EN 61000-6-3 (CIS/H):** Generic emission standard for residential, commercial, and light-industrial environments.
- **IEC EN 61000-6-4 (CIS/H):** Generic emission standard for industrial environments.
- **IEC EN 61000-4-3:** Radiated, radio-frequency, electromagnetic field immunity test.
- **IEC 61000-4-21:** Reverberation chamber test methods.
- **IEC 61000-4-22:** Radiated emissions and immunity measurements in fully anechoic rooms (FARs).

These standards specify the test setup configurations, applicable frequency ranges, and performance criteria used for emission and immunity testing of equipment in a range of different environments.

2.4.3 CISPR 16/22/32 SERIES

The CISPR 16 series of standards is an internationally recognized set of specifications that defines the characteristics, calibration, and performance requirements of EMC measurement apparatus, as well as standardised methods for evaluating electromagnetic emissions and immunity (IEC CISPR 16, 2019). While CISPR 16 encompasses both conducted and radiated disturbance measurements, radiated testing is particularly critical for evaluating the EMC of equipment in the radio frequency (RF) spectrum. CISPR 16 provides detailed guidance on both test site configuration and measurement procedures to ensure repeatability, comparability, and traceability of results across laboratories worldwide.

Building on these measurement principles stated in CISPR 22 and CISPR 32 defines the maximum emission levels for different types of equipment across defined frequency ranges and environments, including residential, commercial, and industrial settings (CISPR, 2015; ‘Electromagnetic Compatibility of Multimedia Equipment – Limits and Methods of Measurement (CISPR 32).’, 2015). In practice, emissions from a DUT are measured using CISPR 16 methods and compared to limits in CISPR 22 or 32 to check compliance and

electromagnetic compatibility. CISPR 16 details “how to measure,” while CISPR 22/32 specify “acceptable levels”(Ott, 2009; Paul, 2006).

CISPR 16 defines detailed procedures for radiated emissions testing:

- **Frequency Scanning:** The device under test (DUT) is analysed across a specific frequency range to detect emissions that surpass threshold limits. The measurement involves quasi-peak, average, or peak detectors, depending on the relevant standard and application.
- **Antenna Polarization:** Tests are carried out with both horizontal and vertical polarizations to detect emissions from all directions, capturing the worst-case emission levels.
- **Test Distance and Height Scans:** For larger DUTs, adjustments are made to the height of both the DUT and the receiving antenna to find the maximum emission points. Modern testing chambers often automate this process with turntables and vertical scanning systems.
- **Environmental Considerations:** To ensure only DUT emissions are measured, background noise, reflections, and transient interferences needs to be minimized.

Radiated emissions testing as specified in CISPR 16 is essential for compliance with international EMC directives and industry-specific standards (Ott, 2009; Paul, 2006).

2.4.4 MIL-STD-461

The MIL-STD-461 standard is a U.S. military requirement that sets EMC specifications for subsystems and components in defence and aerospace industries. It details procedures for measuring and controlling emissions and susceptibility across a wide frequency range, ensuring reliable operation in harsh, congested electromagnetic environments. (Department of Defense, 2015). MIL-STD-461 specifies emission limits to prevent interference and susceptibility standards to withstand external electromagnetic disturbances. Originally specified for military use, its strict testing has influenced commercial sectors like aerospace, rail, and automotive. Many organizations use it as a benchmark for EMC performance in mission-critical systems where failure risks safety or operations. (Paul, 2006; Ott, 2009).

MIL-STD-461 covers a wide range of tests, including:

- **Radiated Emissions** – measuring electromagnetic energy emitted by equipment in free space, typically over 30 MHz to 18 GHz depending on the equipment class.
- **Conducted Emissions** – evaluating emissions along power and signal lines, typically from 10 kHz to 10 MHz for low-frequency power lines, and higher ranges for RF lines.

- Radiated Susceptibility/ Radiated Immunity– determining the equipment’s ability to function in the presence of radiated electromagnetic fields.
- Conducted Susceptibility / Conducted Immunity– evaluating immunity to disturbances on power and signal lines.
- Transient and Pulse Susceptibility – testing responses to electrostatic discharges, lightning surges, or other fast transients.

Testing setups often require anechoic chambers, shielded enclosures, and specialized injection probes to ensure accurate and repeatable measurements across the specified frequency range.

Table 2.1 below gives a comparison between the MIL-STD-461 and CISPR 22/32 Emission Limits.

2.4.5 COMPARATIVE OVERVIEW OF EMC STANDARDS

While IEC 61000, CISPR 16, and MIL-STD-461 all aim for electromagnetic compatibility, they differ in scope, methodology, and application area. The IEC and CISPR standards, aligned with the European EMC directive, mainly focus on civilian products used in residential, commercial, and industrial settings. Conversely, MIL-STD-461 targets military and aerospace systems, which face harsher environmental conditions and require higher reliability. However, their core principles, ensuring measurement consistency, limiting emissions, and validating immunity, are aligned (Paul, 2006; Ott, 2009).

Figure 2.4 shows the different emissions limits for the different standards while Table 2.1 provides a summary of the standards.

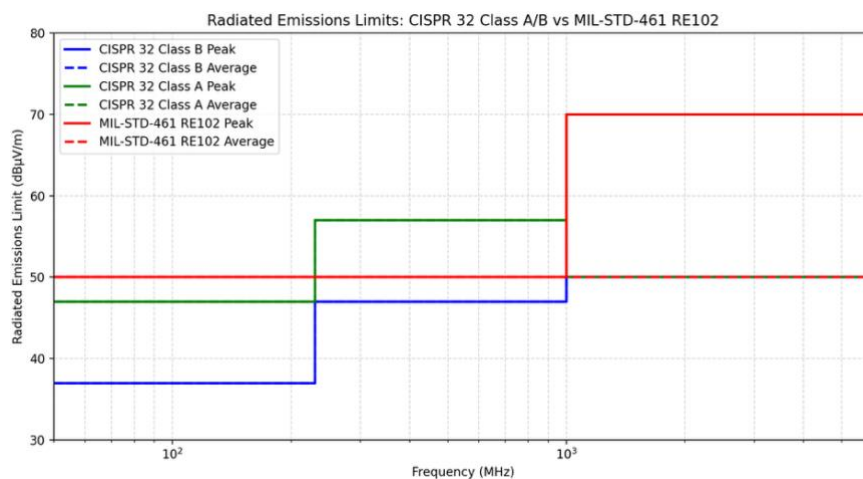


Figure 2.4: Radiated emissions comparison.

Table 2.1: Key EMC standards compared.

Standard	Scope / Environment	Type	Key Description / Application	Representative Limits
IEC 61000-6-3	Residential, commercial, light-industrial	Emission	Radiated and conducted emission limits in non-industrial environments	Radiated: 40–47 dB μ V/m (30–1000 MHz) Conducted: 50–60 dB μ V (10 kHz–10 MHz)
IEC 61000-6-4	Industrial	Emission	Radiated and conducted emission limits in industrial environments	Radiated: 46–53 dB μ V/m (30–1000 MHz) Conducted: 50–60 dB μ V (10 kHz–10 MHz)
IEC 61000-4-3	All	Immunity	Radiated RF electromagnetic field immunity test	3 V/m – 10 V/m (typical)
IEC 61000-4-21	All	Test method	Reverberation chamber test methods	Method standard – no limits
IEC 61000-4-22	All	Test method	Radiated emissions and immunity in fully anechoic rooms	Method standard – no limits
CISPR 16 Series	All	Test equipment / methods	Defines EMC measurement apparatus, procedures, and uncertainty modelling	Method standard – no limits
CISPR 22	IT equipment / residential, commercial	Emission	Radiated and conducted emission limits for information technology equipment	Radiated: 40–47 dB μ V/m Conducted: 50–60 dB μ V
CISPR 32	Multimedia equipment / residential, commercial	Emission	Radiated and conducted emission limits for multimedia equipment	Radiated: 40–47 dB μ V/m Conducted: 50–60 dB μ V
MIL-STD-461	Military / aerospace	Emission & immunity	Comprehensive standard for defence and high-reliability systems, covering radiated/conducted emissions and susceptibility	Radiated: 50–70 dB μ V/m (10 m) Conducted: 50–70 dB μ V Susceptibility: 50–200 V/m

2.5 EMC TEST METHODS

This section covers the test methods used to measure radiated emissions and also briefly touches on conducted emission measurements.

2.5.1 PRE-COMPLIANCE TEST METHODS

Pre-compliance EMC testing allows engineers to identify possible EMI issues before conducting full, expensive compliance tests. This is achieved using simplified measurement setups based on standards like CISPR 22/32, IEC 61000-6-3/4, and MIL-STD-461. These tests identify emissions, susceptibility, and coupling. Early detection can reduce redesign costs, speed up time-to-market, and improve chances of passing EMC compliance tests on the first attempt (Montrose, 2004a; Williams, 2007a; Ott, 2009).

2.5.1.1 NEAR-FIELD PROBING

Near-field probing is a key diagnostic tool in pre-compliance testing used by engineers, is a method where magnetic (H) and electric (E) probes are used to scan PCBs, cables, and enclosures for identification of noise or radiation sources. These probes detect emissions within a few centimetres, allowing engineers to visualize electromagnetic hotspots. By using a spectrum analyser or a real-time EMI receiver in conjunction with near-field probes, designers can isolate problem areas, evaluate the effectiveness of grounding and shield strategies, and validate filtering improvements (Siglent Technologies, 2017).

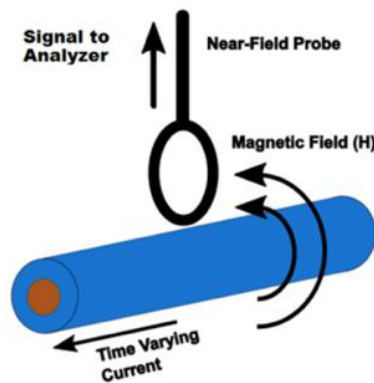


Figure 2.5: Magnetic field probe orientation (from Siglent, 2017).

Although not a substitute for far-field compliance measurements, near-field scanning is instrumental in root-cause analysis and iterative design debugging (Ott, 2009; EMC FastPass, 2018). Near field probes are commercially available however a simple H-field probe can be made using a small loop of conductive wire that senses the magnetic field generated by current-carrying traces or components. To build one, a short length of semi-rigid coaxial cable (e.g., RG-405) is used; the outer conductor is stripped back at the end, and the inner conductor is bent into a small loop, typically 5–10 mm in diameter, before being soldered to the shield to close the loop. The smaller the loop, the better the spatial resolution, though sensitivity decreases. The other end of the cable is fitted with an SMA connector for connection to a spectrum analyser or oscilloscope. To reduce E-field coupling, the loop can be shielded using conductive tape or copper foil, leaving only a small gap opposite the loop opening to maintain magnetic sensitivity. The probe can then be calibrated using a known current loop or used directly for qualitative near-field scanning of PCBs and cables (Siglent Technologies, 2017).

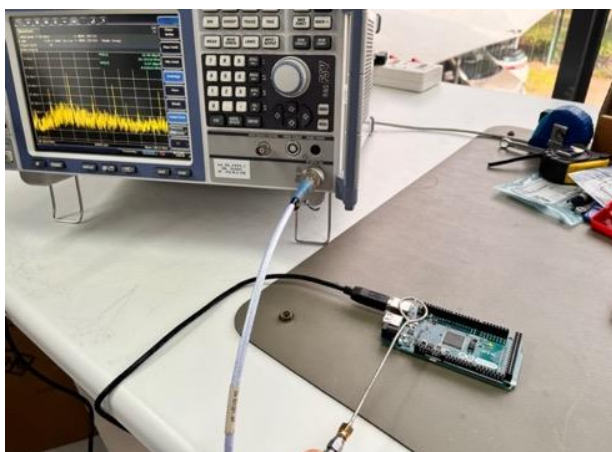


Figure 2.6: Home-made near field probe.

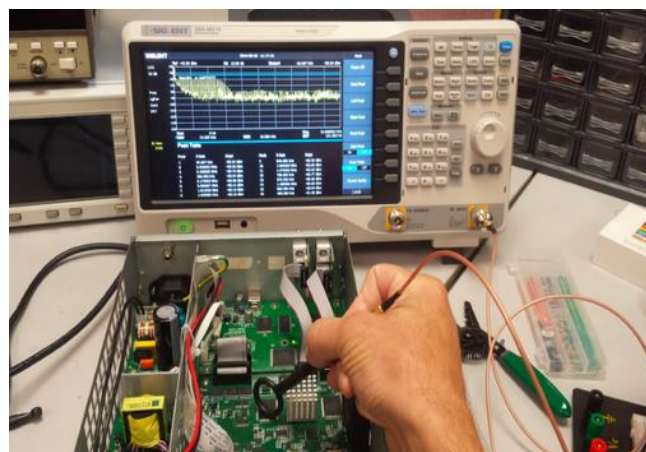


Figure 2.7: Commercial near field probe (from Siglent, 2017).

2.5.1.2 COMMON-MODE CURRENT MEASUREMENTS

Another important aspect of pre-compliance testing involves measuring common-mode (CM) currents on cables and harnesses. CM currents, flows in phase and equal on multiple conductors relative to ground. They significantly contribute to radiated emissions, between 30 MHz and 300 MHz. To measure CM currents, engineers use a current clamp probe around power or signal cables connected to the equipment being tested. The probe output, in dB μ V and is analysed with a spectrum analyser over the frequency range of concern. Then by using the probe's transfer impedance, these values estimate the radiated field strength in open area tests (Montrose, 2004a). Controlling common-mode currents is important as microamp-level currents can cause radiated emissions along long cables or on metallic structures. Early identification allows the implementation of shielding improvements before testing, (Paul, 2006).

Pre-compliance EMC testing provides a more cost-effective, iterative, and diagnostic approach to EMC assurance.

2.5.2 RADIATED EMISSIONS TESTING

Radiated emissions testing measures the unintentional electromagnetic radiation emitted from the DUT. The measurement setup generally involves a calibrated receiving antenna, such as a biconical or log-periodic antenna, placed at a specified distance typically 3 m or 10 m depending on the test standard (CISPR 16-1-4; CISPR 22/32; IEC 61000-6-3/4). The EUT is mounted on a non-conductive turntable to allow 360° rotation, ensuring emissions are captured from all orientations, and the antenna height is varied from 1 m to 4 m to detect the maximum field strength. Measurements are performed across a defined frequency range, often 30 MHz to 1 GHz for most commercial products and up to 6 GHz or higher for high-speed digital

equipment. It is important to understand the difference between near-field and far-field regions when performing radiated measurements. The near-field is the region close to the source, typically within a few wavelengths, where the E and H fields are not purely radiative and their amplitudes and phases vary with distance and orientation. In this region, emissions are strongly influenced by the geometry of the source. The far-field, at distances several wavelengths from the source, is where the EM fields propagate as plane waves and the ratio of E to H fields becomes constant. Regulatory radiated emission limits are defined in the far-field, and measurements at 3 m or 10 m distances ensure compliance with these standards. Data obtained are compared to the emission limits specified by the relevant standard; for example, CISPR 32 Class B (residential) imposes stricter limits than Class A (industrial) to ensure compatibility with sensitive communication devices (Montrose, 2004a; EMC Fast Pass, 2018) (Hegarty, 2018).

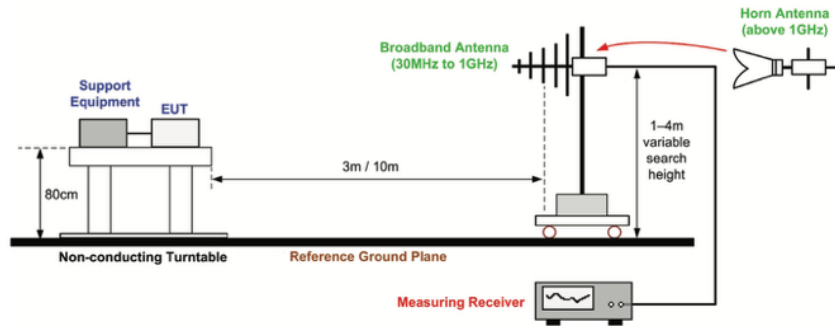


Figure 2.8: CISPR test setup (from Hegarty, 2018).

Figure 2.9 (Smit, 2020) shows a practical test setup used for evaluating systems developed for the MeerKAT radio telescope. This setup is for testing in the SARA0 reverberation chamber and is generally used to conduct RFI and EMC qualification. A Tektronix RSA5115B Real-Time Spectrum Analyzer (RTSA) Functions as the main receiver, collecting emission data over a default frequency range from 70 MHz to 6 GHz. The default frequency range has been defined as operational capabilities of the chamber and test equipment. Measurement data are recorded via the I/Q outputs of the RTSA for subsequent post-processing and analysis using SARA0's IDL-based software backend.

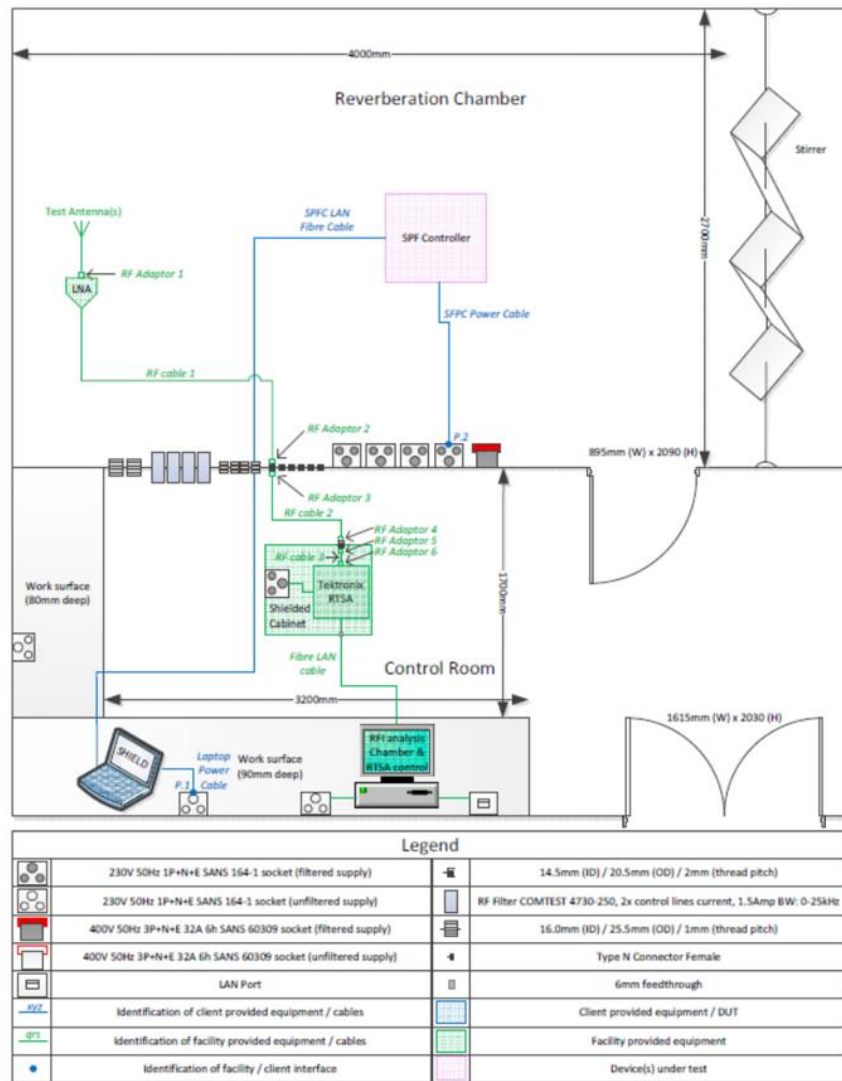


Figure 2.9: Emissions test setup (from Smit, 2020).

2.5.3 RADIATED IMMUNITY TESTING

Electronic systems face electromagnetic fields from sources like radio transmitters, mobile phones, and power supplies. Radiated immunity testing checks if an EUT works correctly under RF electromagnetic fields, ensuring reliable operation and detecting susceptibilities that could cause malfunctions. Conducted in shielded chambers, a transmitting antenna radiates the DUT with known field strengths (3 V/m to 30 V/m) over a frequency range (80 MHz to 6 GHz) per IEC 61000-4-3 and MIL-STD-461. The EUT's is monitored and any errors and irregularities are recorded and categorized according to severity (EMC Fast Pass, 2018)(Williams, 2007b). A practical example of radiated immunity or susceptibility test setup is shown in Figure 2.10 (Smit, 2020), where the radiated susceptibility of a Single Pixel Feed Controller (SPFC) used in the SKA radio telescope is evaluated. The testing procedure, as defined in MIL-STD-461, was conducted as follows. The radiated susceptibility setup was first verified to be fully operational, with the signal generator connected to the transmit antenna and the Tektronix

RSA5115B Real-Time Spectrum Analyzer connected to the receive antenna. A baseline measurement was then performed with the SPFC powered off, followed by calibration of the setup in accordance with the “Receive Antenna” procedure outlined in Section 5.20.4.4 of MIL-STD-461. The signal generator output was adjusted to ensure that the electric field strength at the device under test exceeded the IEC 61000-6-4 emission limits with an appropriate margin.



Figure 2.10: Susceptibility test setup. (from Smit, 2020).

The SPFC was operated under operational load conditions with continuous monitoring of its voltage, current, and temperature sensors to identify possible signs of electromagnetic susceptibility. The same approach was used for the conducted susceptibility test, where a signal generator was connected to an EMI injection clamp and an RTSA was attached to a current clamp. The generator was set to sweep across the specified frequency range while producing a calibrated RF output power between +10 dBm and +15 dBm. During both tests, signal levels received and SPFC telemetry data were recorded and analysed for any anomalies that might suggest performance issues caused by electromagnetic interference. (Smit, 2020).

2.5.4 TEST SITES

When conducting the EMC tests, as mentioned in section above, isolating the test environment from the outside electromagnetic environment is required. Suppose randomly varying ambient signals are allowed to mix with the signals of interest from the DUT; it will be time-consuming and virtually impossible to separate the signals to be measured to the levels required by the specifications (Morgan, 2007). Therefore, it is required and stipulated in the standards to perform these tests in isolated environments. This section covers the types of shielded environments for EMC testing.

2.5.4.1 STANDARD SHIELDED ENCLOSURES

Standard shielded enclosures provide a cost-effective solution for controlling EMI during early-stage testing or basic EMC evaluations. Typically constructed from wood frames and thin

sheet metal panels, these enclosures are modular, allowing flexible sizing and easy assembly or disassembly. The shielding effectiveness (SE) of standard screened rooms varies significantly depending on construction quality, panel thickness, and joint continuity, typically offering around 60–80 dB of attenuation across frequencies from 30 MHz to 18 GHz, an example of a shielded chamber SE testing in progress is illustrated in Figure 2.11. While suitable for preliminary testing, these enclosures can generate standing waves due to reflective surfaces, introducing measurement uncertainty (Smit, 2020) it is recommended that pre-compliance test also be performed inside of a shielded chamber to prevent external sources coupling on to the DUT.



Figure 2.11: EMSS shielded chamber.

2.5.4.2 ANECHOIC AND SEMI-ANECHOIC CHAMBERS

Anechoic Chambers (ACs) are high-performance EMC test environments in which all reflective surfaces are lined with radio-absorbent material (RAM) as shown in Figure 2.12 to suppress reflections and provide a near free-space environment. ACs typically achieve SE of 80–100 dB across a wide frequency range (30 MHz – 18 GHz), making them ideal for precise radiated emissions and immunity measurements. Semi-Anechoic Chambers (SACs), on the other hand, retain a conductive ground plane while covering walls and ceilings with RAM.

This configuration provides SE of 70–90 dB across most test frequencies and balances cost with measurement accuracy. Both ACs and SACs reduce standing waves and prevent modal patterns, but full RAM-lined chambers are expensive and reduce usable working space, making them suitable primarily for industries or standards that justify the investment. SACs, with RAM applied selectively, mitigate the worst effects of standing waves while offering a more practical solution for reliable EMC measurements in industrial and residential applications, including CISPR 32 Class A/B compliance testing (Morgan, 2007).

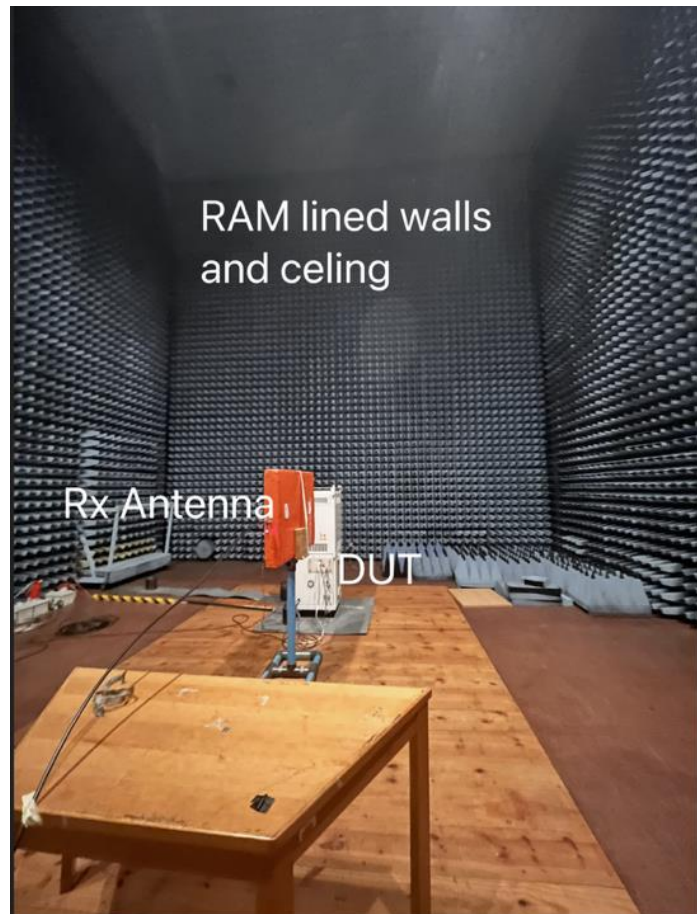


Figure 2.12: Houwtec anechoic chamber.

2.5.4.3 REVERBERATION CHAMBERS

The concept of a reverberation chamber, also known as a stirring mode chamber, provided a low-cost alternative to semi-anechoic chambers. Standing waves inside reflective screed rooms create measurement uncertainty and are overcome by deliberately maximizing the number of possible reflection modes in a highly reflective chamber. This exposes the EUT to all possible field strength values at the frequencies of interest in the band being investigated. This type of test environment consists of a reflective enclosure with numerous irregular shaped and sized paddle wheels (also referred to as a stirrer as shown in Figure 2.13). These paddle wheels are fixed to the walls and/or ceiling and are driven by stepper motors. This ensures that the

maximum number of possible chamber modes are activated Reverberation Chambers can achieve effective isolation from external EMI in the order of 50–80 dB, depending on wall construction and chamber design. They excel at generating high, uniform field strengths inside the chamber, ideal for susceptibility testing under MIL-STD-461 or aerospace standards (Morgan, 2007).

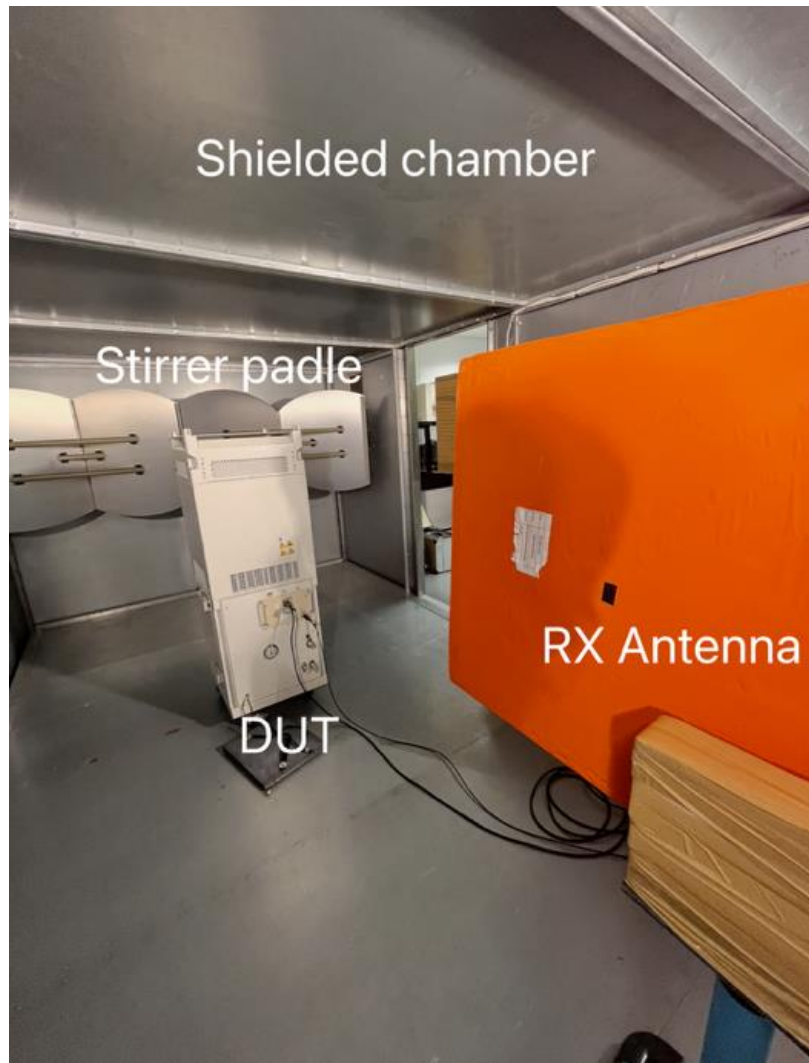


Figure 2.13: SARAO reverb chamber.

2.5.4.4 OPEN AREA TEST SITES

OATS are traditional outdoor test sites that rely on natural isolation and distance from noise sources rather than active shielding. While they do not provide inherent shielding, the combination of a ground plane and site selection in low-noise areas can achieve an effective shielding effect equivalent to 30–50 dB at lower frequencies. OATS are particularly useful for large equipment or low-frequency radiated emissions where chamber constraints are limiting (IEC CISPR 16, 2019).

Table 2.2: Test site comparisons.

Test Environment	Description	Shielding Effectiveness (SE)	Typical Frequency Range	Applications / Standards
Standard Shielded Enclosure	Wood/metal modular panels, low-cost setup	20–60 dB	30 MHz – 1 GHz	Preliminary pre-compliance EMC tests
Anechoic Chamber (AC)	Fully RAM-lined; minimal reflections	80–100 dB	30 MHz – 18 GHz	CISPR 16/32, IEC 61000-6-x, precise radiated measurements
Semi-Anechoic Chamber (SAC)	Ground plane retained; RAM on walls/ceiling	70–90 dB	30 MHz – 6 GHz	Industrial and residential EMC testing, Class A/B compliance
Reverberation Chamber (RC)	Reflective walls with mode stirrers	50–80 dB	80 MHz – 18 GHz	MIL-STD-461, susceptibility and immunity testing
Open Area Test Site (OATS)	Outdoor site with line-of-sight	30–50 dB	30 MHz – 1 GHz	Large DUTs, low-frequency radiated testing, CISPR 16-1-4

2.6 ANTENNA TEST STANDARDS

The *IEEE Std 149-1979 standard test procedures for antennas* are comprehensive and comprise of recommended practices for measuring antenna transmitting and receiving properties. The following topics and sections of this standard apply to this study:

2.6.1 RANGE MEASUREMENTS OF ANTENNA RADIATION PATTERNS

In order to completely characterize the radiation field of an antenna, it is required to measure the antenna's relative amplitude, relative phase, polarisation and power gain on the surface of a sphere, with the centre of the sphere located at the antenna under test as shown in Figure 2.14. Antenna radiation pattern is defined as the representation of these radiation properties as a function of space coordinates and describes how an antenna radiates or receives energy. Since the antenna under test is at a fixed distance from the measuring point, only the two angular coordinates are variables in a given radiation pattern. It is impractical to completely measure the radiation pattern of an antenna; therefore, a sampling technique is used where the polarisation and frequency of operation are fixed, and the θ coordinate can be varied. For each increment of θ , the desired antenna property can be measured over the range of ϕ , resulting in a complete antenna pattern (IEEE Standards board, 2008).

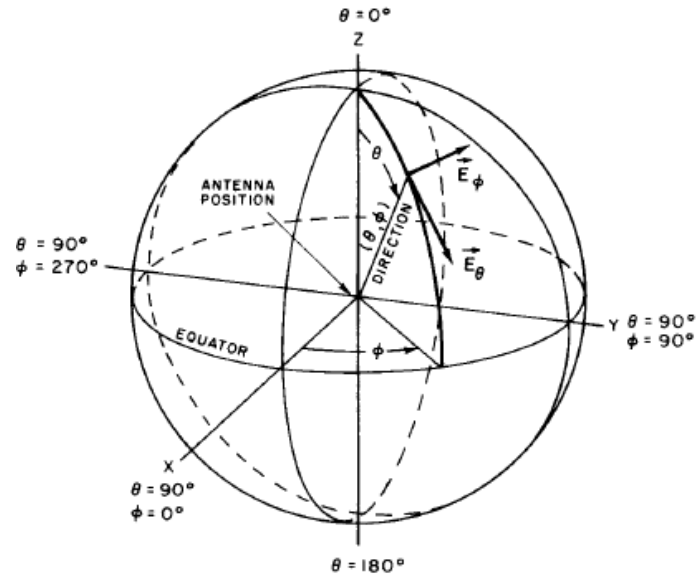


Figure 2.14: Spherical coordinate system for antenna measurements (from IEEE Standards board, 2008).

Antenna ranges have been developed to measure antennas independent of their operational environments. Two basic antenna range configurations accomplish the requirements to measure antenna radiation patterns.

Fixed-line of sight is a configuration where the test antenna is rotated around a suitable axis, and the source antenna is located at a fixed point.

Movable line of sight is another configuration used. The source antenna is moved incrementally and or continuously along the circumference of a circle, with the circle centred at the phase centre of the antenna under test (IEEE Standards board, 2008). When measuring the radiation characteristics of an antenna, the ideal incident field for measurements is that of a uniform plane wave. However, it is only possible to approximate such a field in practice. Moreover, attempts to create a uniform plane wave have led to the development of two basic range types.

Free space ranges: These ranges are designed to suppress all the possible effects of the surroundings to tolerable levels. Examples are anechoic chambers, elevated and slant ranges.

Reflection ranges: these ranges make use of reflections to produce an approximated plane wave. Furthermore, ground reflection ranges use the energy that's specularly reflected from the range surface to create interference with the direct energy path of the antenna being tested (Kummer and Gillespie, 1978; IEEE Standards board, 2008).

2.6.2 MEASUREMENT OF POWER GAIN AND DIRECTIVITY

For this research, the measurement of power gain and directivity of an antenna is of interest as these are the most common antenna measurements to be performed. As stated by (IEEE Standards board, 2008), the techniques used to determine the power gain of an antenna depend

on the frequency of operation. Ground reflection ranges are mainly required for measurements between 0.1 – 1 GHz as free space conditions become challenging to simulate. Microwave measurement techniques are less practical at these frequencies. The *gain-transfer* method or *gain comparison* method is primarily used to measure the power gain of an antenna. This method compares the gain of the antenna under test to that of a gain standard antenna. The directivity of the antenna under test can then be found by integrating the far-field radiation patterns of the antenna under test over a closed spherical (Kummer and Gillespie, 1978; IEEE Standards board, 2008).

2.6.3 POSITIONING SYSTEMS

As seen in the section above, in order to test antennas according to the *IEEE Std 149-1979* standard, positioning systems are required to rotate the antenna under test through the θ and ϕ (azimuth) rotational axis as shown in Figure 2.15 (IEEE Standards board, 2008). However, only rotation through the ϕ (azimuth) axis will be considered in this study.

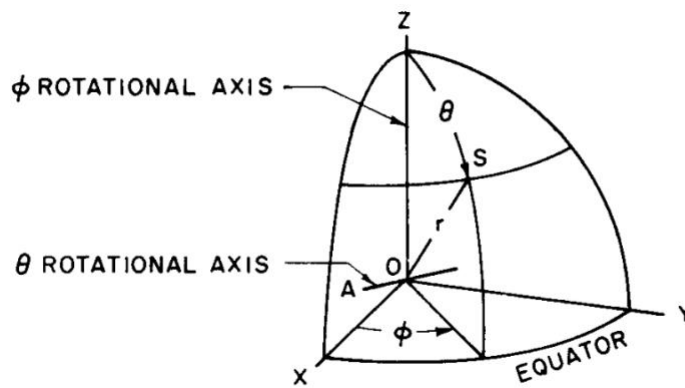


Figure 2.15: Rotation required for positioning systems (from IEEE Standards board, 2008).

2.7 TEST STATION TURNTABLES

Multiple EMC and Antenna test methods include the rotation of a DUT, for example, when performing a radiated emission test at an OATS as defined in CISPR 16-1-4, it mandates the rotation of the DUT through 360° because emissions from DUT can be directional, and emissions do not extend in a uniform sphere from the DUT. There tends to be an orientation of the DUT at which the highest field strength is produced. As shown in Figure 2.16, a turntable rotates the DUT through 360° and presents the DUT to the measurement antenna at every angle (Wibowo *et al.*, 2010).

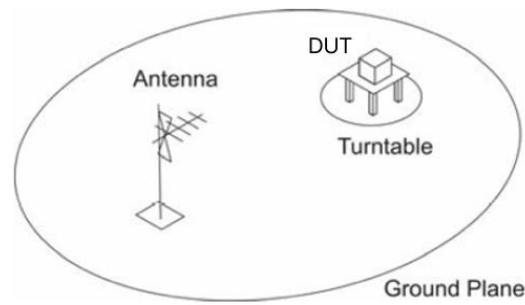


Figure 2.16: OATS Radiated emissions test configuration (from Wibowo et al., 2010).

The basic requirements of a turntable are: It should not interfere with measurements taken. It should be able to rotate the DUT through 360° on its azimuth axis, and the rotation should be controlled remotely. The turntable must be capable of supporting the weight of a DUT and any auxiliary equipment (Montrose, 2004b).

For the purpose of this research, a turntable design with a weight limit of 25 kg will be considered. There are generally two types of turntables used for EMC and Antenna testing: floor standing and table-top units; Floor-standing units should be constructed out of metal and installed level to the ground plane of the shielded room. The turntable should be bonded to the ground plane. Flexible gaskets or shims generally provide this connection. Table-top turntable systems should be non-conductive and non-metallic and should be positioned on top of the ground plane. The table on which table-top equipment is to be installed must be non-metallic and at the height of 0.8 m above the ground plane (Montrose, 2004b). There are multiple commercially of the shelf turntables available. The technical specifications of these turntables will be used to formulate the design specifications for this research.

Example 1: CTE0500 Compact table from Innco-systems

The CTE0500 turntable manufactured by Innco-Systems shown in Figure 2.17 is a compact and low-cost floor standing turntable and is rated for test equipment up to 25 kg. A clamp on the centre rod allows the height of the turntable to be adjusted. The drive unit is located at the bottom of the assembly and can be covered with floor RAM. The CTE0500 can be easily disassembled and transported; refer to Table 2.3 for technical specifications. (Innco-systems, 2021)

Example 2: TT03 PF turntable from Maturo

The TT 0.3 PF turntable manufactured by Maturo is an example of a table-top turntable, as is shown in Figure 2.18. The rotating plate/surface is constructed from rigid PVC integral skin foam sheets. The table has an opening in the centre of the table for inserting power supply or monitoring cables. The turntable has an IEEE 488.2 (GPIB) bus that provides remote control options. Refer to Table 2.3 for technical specifications (Maturo, 2021).



Figure 2.17: Turntable example 1.



Figure 2.18: Turntable example 2.



Figure 2.19: Turntable example 3.

Example 3: TTW-104 motorized turntable from COM-POWER corporation

TTW-104 turntable manufactured by Com-Power shown in Figure 2.19 is a floor standing or above ground motorized turntable. The table is constructed with wood coated with weather-resistant laminates for outdoor or indoor use. The TTW-104 platform is 1200 mm in diameter and has a rotation drive that consists of a 1/15 HP motor and gear reduction drive. The turntable has a load capacity of up to 455 kg with an evenly distributed load. The turntable is supplied with a remote switch to change the direction of rotation during the test. Refer to Table 2.3 for more technical specifications. A wooden table can be installed on this platform for desktop testing (POWER, 2021).

Table 2.3: COTS turntable specifications.

Specification	Example 1	Example 2	Example 3
Part Number:	CTE0500	TT03	TTW-104
Manufacturer	Innco-systems	Maturo	COM-POWER
Diameter	500 mm	300 mm	1200 mm
Permissible Load Max.	25 kg	50 kg	455 kg
Max. Height 1100 Mm	1100 mm	190 mm	230 mm
Material Carrier Plate	N/A	PVC integral skin-foam sheets	N/A
Min. rpm	0.5 rpm	0.5 rpm	2.1 rpm
Max. rpm	2.0 rpm	3 rpm	
Positioning Accuracy	+/-1°	+/- 0.5°	N/A
Rotating Angle	±200° or -20° to +380°	+400°/-200°	N/A
Control	Fibre optic lines	Fibre optic lines	Copper cable
Motor	Electronic EC motor 150W	Brushless DC motor 200 W	1/15 HP
Drive Unit Interference Suppression	Shielded and radio interference suppressed; 20 dB	20 dB as per EN 55022 class B	N/A
Power Supply	Voltage 115 / 230V (50- 60Hz)	208-230 VAC, 50/60 Hz, 2A max	115 V AC, 60 Hz
Cost	Estimated price range: €6,000 - €10,000	Estimated price range: €4,000 - €6,000	Estimated price range: \$3,000–\$5,000

Commercial EMC turntables, while precise and convenient for automated measurement setups, are generally unsuitable for sensitive pre-compliance or diagnostic testing due to their inherent electromagnetic emissions. These emissions originate from internal motors, power supplies, and control electronics operating at high voltages and currents. All 3 models covered use electronic or brushless DC motors (150–200 W) powered by 115–230 V AC. Even though manufacturers often include shielding and interference suppression rated around 20 dB (per EN 55022 Class B), this attenuation is insufficient for low-noise near-field or radiated emissions investigations where background noise must remain several tens of decibels below the DUT emissions. Many commercial turntables use copper-based control cables rather than fibre optics, creating potential coupling paths for conducted and radiated noise. For precision diagnostic work, non-motorized or manually driven, low-emission rotating platforms are therefore preferred to maintain a clean electromagnetic environment.

2.7.1 TURNTABLE CONTROL SYSTEM

Figure 2.20 shows a block diagram of a basic turntable control system. in (Wibowo *et al.*, 2010), they present a turntable control system designed for use in an OATS. An operator inputs the required speed and angle of the turntable via a keypad. A microcontroller then processes the input data, and the settings are displayed on an LCD. The stepper motor is rotated by a microcontroller and a stepper motor driver. The rotation speed is controlled using a traditional pulse with a modulation signal generated by the microcontroller.

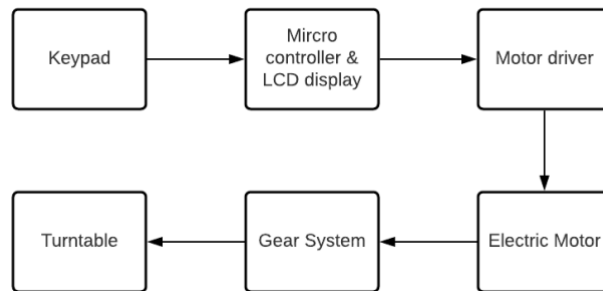


Figure 2.20: Turntable control system block diagram (adapted form Wibowo et al., 2010).

A block diagram of an alternative drive method that can be utilised as a turntable control system is presented in Figure 2.21. This design by (Marais, Rensburg and Matthysen, 2018) has been used in the radio astronomy field and is a proven reduced emissions design. The operator inputs the required speed of the stepper motor via a computer. An field programmable gate array (FPGA) then processes this input, and two orthogonal sinusoidal signals are generated and filtered. These signals are then amplified with an analogue power amplifier and supplied to the stepper motor. The rotation speed can be controlled by varying the frequency of the generated sinusoidal signals.

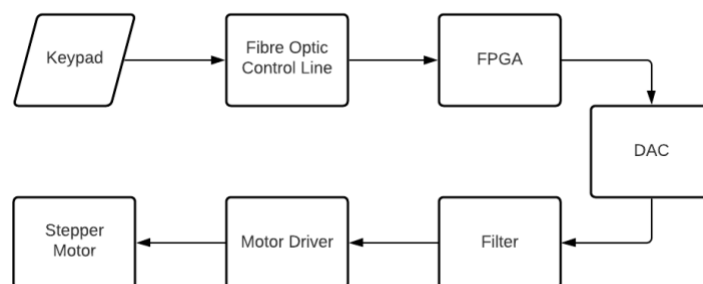


Figure 2.21: FPGA-based stepper motor control (adopted from Marais, Rensburg and Matthysen, 2018)

Building on turntable control methods like microcontroller-based pulse with modulation (PWM) and FPGA sinusoidal drives, precise motion control remains essential for accurate

EMC and antenna measurements. The following sections therefore examine the main theoretical concepts required to design and implement a test turntable.

2.8 ELECTRIC MOTORS

Electric motors form the foundation of motion control, providing the mechanical drive required for systems such as antenna positioners, turntables, and precision instrumentation mechanisms. The selection of an appropriate motor is determined by the position accuracy, torque, and speed requirements of the application. Apart from mechanical performance, the EMI generated by a motor and its control electronics influences the overall characteristics of the system. Understanding the electrical and magnetic characteristics of various motor types is therefore essential for designing systems that operate reliably within RFI-sensitive environments. According to (Hughes and Drury, 2019) an electric motor is an electrical machine that converts electrical energy into mechanical energy. Figure 2.22 illustrates this principle involves producing torque via interaction between the stator's radial magnetic flux and the rotor's axial current-carrying conductors. When a conductor with current is in a magnetic field, it experiences a force according to the Lorentz force equation.

$$\mathbf{F} = I(\mathbf{L} \times \mathbf{B}) \quad (2.2)$$

where:

I = current through the conductor

$\mathbf{L}$ = length vector of the conductor

$\mathbf{B}$ = magnetic flux density

This force acts tangentially to the rotor, creating torque that drives rotation. It is strongest when the magnetic field is perpendicular to the conductor. Magnetic flux, or “excitation,” can come from permanent magnets or an external energized field winding, as shown in Figure 2.22.

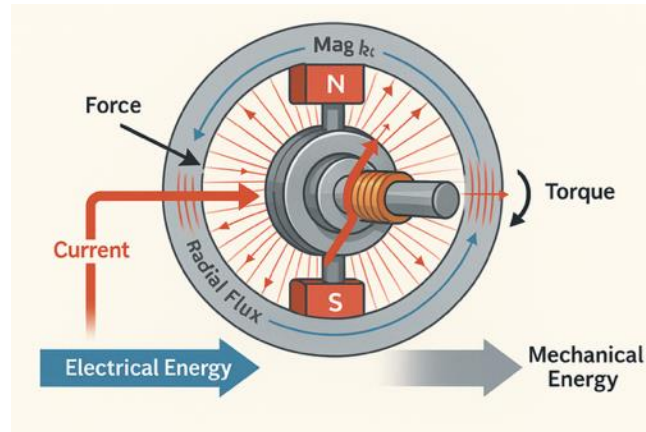


Figure 2.22: Motor operation.

A few types of motors suit environments that need minimal EMI. Brushed or commutator motors produce broadband noise from arcing and contact fluctuations, thus they are unsuitable for low EMI applications. According to (Armstrong, 2006f) brushless DC (BLDC) and stepper motors are the most suitable options for low-EMI operation, as they generate minimal electrical noise, while maintaining precise torque and position control. The subsequent sections cover the operating principles, control methods, and EMI features of these motors, emphasising their performance, emission behaviour, and suitability for low-EMI applications.

2.8.1 BRUSHLESS DC MOTORS / ELECTRONIC COMMUTATED MOTORS

(Mazurkiewicz, 2000) describes brushless DC (BLDC) motors, also known as electronically commutated motors, as advanced electric motors offering benefits over traditional brushed DC motors. Unlike brushed motors that use mechanical brushes and a commutator, BLDC motors rely on electronic commutation. A BLDC motor rotor contains permanent magnets, while the stator has windings energized in sequence by an electronic controller to create a rotating magnetic field, this results in continuous torque and smooth rotation. Rotor position is generally detected using Hall effect sensors or by sensing back EMF. BLDC motors are more efficient and have longer lifetimes because they lack brushes that cause friction. Speed is typically controlled via PWM. While inherently reducing EMI from brushes, high-frequency switching can generate conducted and radiated EMI. These motors offer higher torque, speed, smoother operation, lower noise, and a more compact design than brushed motors.

2.8.2 STEPPING MOTORS

Stepper motors are electromechanical devices that convert electrical pulses into precise mechanical motion. Unlike conventional motors that rotate continuously when powered, stepper motors can move in discrete steps, allowing precise control of position and speed (Components 101, 2024). This non continuous movement is very useful in 3D printing, CNC,

robotics, and automation. A stepper motor consists of a rotor (permanent magnets) and a stator with coils. The coils are energised to create a magnetic field that aligns the rotor. Sequential energisation of the stator coils produces non continuous or stepwise rotation, where the step angle is determined by the motor's design. Stepper motors are categorised as unipolar or bipolar, unipolar stepper motors have centre-tapped windings, typically with four or five wires, and are easier to drive because only one half of each coil is energised at a time. This sequential energisation produces stepwise rotor movement, though unipolar motors deliver lower torque. Bipolar stepper motors, on the other hand, have two independent windings per phase with no centre tap and require current reversal through each winding to operate. While their control circuitry is more complex, bipolar motors offer higher torque and more efficient operation. Both types convert electrical pulses into precise rotational steps, making them suitable for applications where accurate positioning is essential.

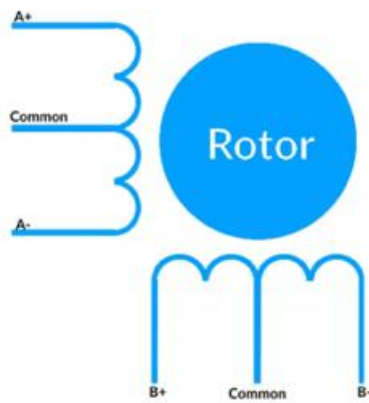


Figure 2.23: Unipolar stepper motor (adopted from Components 101, 2024)

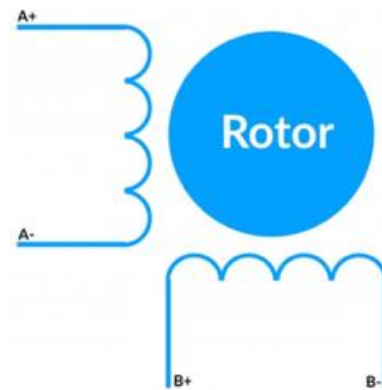


Figure 2.24: Bi polar stepper motor (adopted from Components 101, 2024)

Control of stepper motors is typically open-loop, with pulses sent to the motor driver to advance the rotor by a specific number of steps. Advanced applications may use micro stepping, where current is divided across windings to achieve smaller step increments, smoother motion, and reduced vibration. Stepper motors produce less inherent EMI compared to brushed motors since there are no brushes. However, rapid switching of coil currents can generate high dI/dt , producing conducted and radiated EMI. Proper driver design, careful wiring, and filtering are often required to minimise EMI, especially in sensitive electronics environments. Common stepper motor sizes include NEMA 17, NEMA 23, NEMA 14, and 28-BYJ48, each chosen based on torque, size, and application requirement

Table 2.4: BLDC vs stepper motor comparison.

Feature	BLDC Motor	Stepper Motor
Operating Principle	Continuous rotation using rotor permanent magnets and stator windings; electronic commutation	Discrete rotation; rotor aligns with sequentially energized stator windings
Control Method	ESC required; sensed (Hall effect) or sensor less (back EMF); speed controlled via PWM; advanced control via FOC	Typically open-loop; unipolar or bipolar; micro stepping for smoother motion
Torque Characteristics	High torque-to-weight ratio; smooth at high speed; torque may drop at low speeds without current control	High holding torque at low speeds; torque drops at higher speeds; step angle determines resolution
Speed Range	High-speed capable; continuous operation	Moderate speed; limited by step rate and resonance
Efficiency	High; no friction losses from brushes	Moderate; energy lost to detent torque and winding resistance
EMI Characteristics	Brushless design reduces sparking; high-frequency PWM switching can generate EMI	Less inherent EMI; rapid coil switching can produce conducted and radiated EMI
Complexity	Requires electronic controller; more complex drive electronics	Simpler (especially unipolar); bipolar requires more complex driver
Cost	Higher initial cost; lower maintenance	Lower cost; simpler construction; easy maintenance
Applications	Drones, electric vehicles, robotics, fans, pumps	3D printers, CNC machines, robotics, automation systems

From Table 2.4 above it can be seen that for the purpose of this research a stepper motor will be the best option to use, as its more cost effective and has less risk associated with EMI if a correct motor driver is selected.

2.9 MOTOR DRIVE SYSTEMS

Motor drives, are electronic devices that control the speed, torque, and direction of electric motors. These systems are used in various applications, from industrial machinery to household appliances like air conditioners and washing machines (ABB, 2023) At their core, motor drives regulate the electrical energy supplied to motors, modifying input power to achieve desired motor performance. In an AC drive, AC voltage is rectified into DC and then converted back into AC with a variable frequency, allowing for precise control of motor speed and torque. Advanced drives use complicated electronics for accurate control, feedback and optimisation (Nidec, 2021)(Matan, 2024).

2.9.1 TRADITIONAL STEPPER MOTOR CONTROL

Stepper motors use techniques like wave drive, full-step, half-step, and microstepping for precise control. For wave drive, one phase energises at a time, moving the rotor stepwise. Full-step mode energizes two phases simultaneously, increasing torque while maintaining a stepwise motion. Half-step mode alternates between single and dual-phase energization, effectively halving the step size for finer resolution, though torque fluctuates between high and low depending on the number of active phases. Micro stepping further increases positional resolution by gradually varying current in each phase, producing intermediate rotor positions between full steps. While micro stepping enables very smooth motion and high precision, it requires more sophisticated driver circuitry and reduces torque per step (Baluta, 2007; Condit *et al.*, 2024).

In the following sections, two stepper motor drivers used for controlling motors in the SKA and MeerKAT radio telescopes are evaluated. These drivers were specifically designed to operate in environments with extremely stringent electromagnetic interference (EMI) requirement and is the most applicable to this research.

2.9.2 DRV8818 BASED STEPPER MOTOR DRIVER

A COTS low EMI/RFI stepper motor driver (Liebenberg and Marais, 2013), based on the Texas Instruments DRV8818 stepper motor controller IC, is employed in the MeerKAT L-band and UHF-band receivers, both of which use the same cryocooler stepper motor. The DRV8818 can drive bipolar stepper motors with currents up to 2.5 A per phase. Its low output-stage resistance ($0.37\ \Omega$) minimizes temperature rise compared to drivers with higher resistance. The IC includes an integrated micro stepping indexer capable of up to 1/8 stepping, discretizing the ideal sinusoidal current waveform into eight levels. Each STEP input pulse advances the output currents through an internal lookup table. For example, achieving 60 rpm at 1/8 stepping requires a STEP frequency of 1.6 kHz. Current is maintained at the desired level using fixed off-time PWM, with voltage sensed across series resistors in the motor windings providing feedback for PWM control. The motor winding inductance and resistance, combined with the drive voltage, determine the rate of current change and ripple for a fixed PWM period. A simplified block diagram of the DRV8818 output stage is shown in Figure 25.

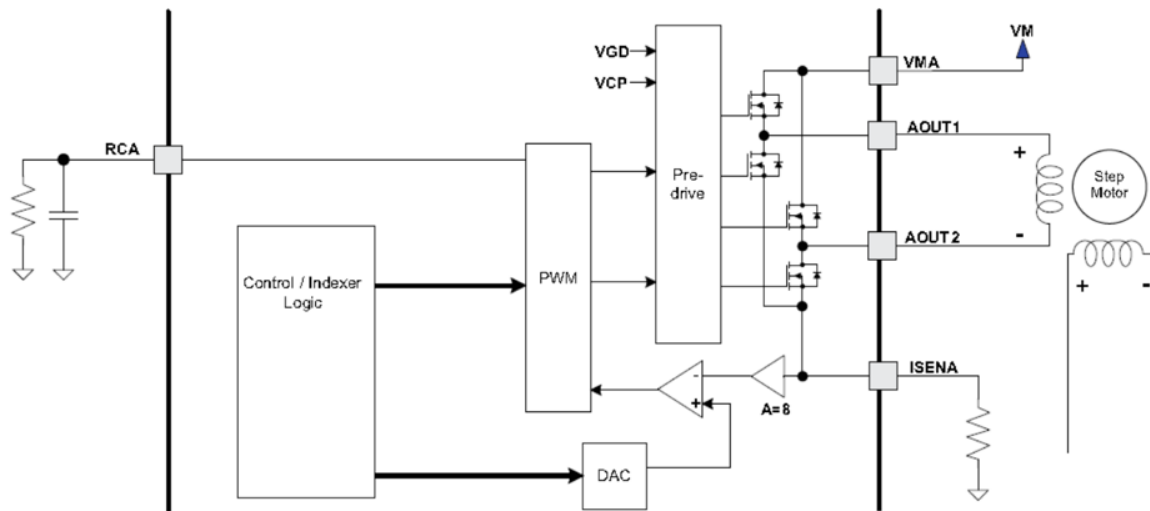


Figure 2.25: Simplified block diagram of the DRV8818 output stage (adopted from Liebenberg and Marais, 2013).

To reduce high-frequency content in the driving signals, the output is low-pass filtered. Since the PWM relies on the motor's inductance to smooth current, shunt capacitance alone cannot be used without causing excessive ripple. Instead, an LC low-pass filter is implemented, where series inductors replace the motor's inductance to control PWM rise time, allowing the use of filtered connectors for signal exit. In the first stage, L1, L2, and C1 set the lowest cut-off frequency while limiting ripple through these components. The second stage uses ferrite chips (L3–L6) and capacitor C2, together with connector capacitance, to attenuate high-frequency noise not filtered in the first stage. Common-mode capacitors (CCM, 100 pF) connected to ground further suppress high-frequency common-mode EMI. These components are carefully selected to account for non-ideal behaviours such as self-resonance of inductors and parasitic effects of capacitors

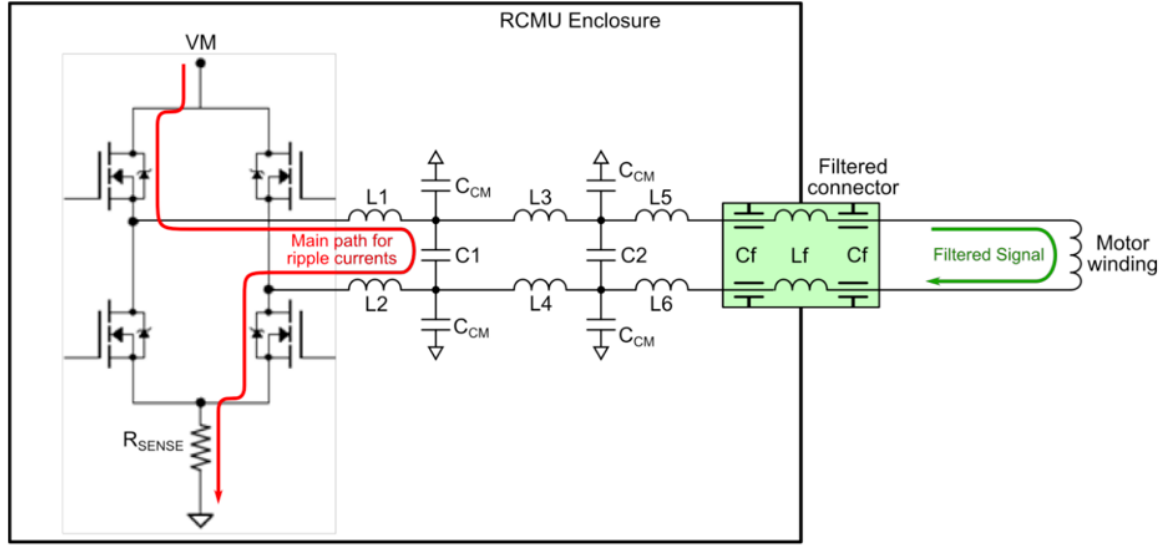


Figure 2.26: Low-pass filtering of the stepper motor driving signals.

(adopted from Liebenberg and Marais, 2013).

While this design employs a conventional stepper motor IC, effective EMI reduction techniques are integrated. However, it must be used in combination with additional measures such as shielding and system-level filtering for optimal performance. (Liebenberg and van Staden, 2018) recommends that The recommended input filters are TUSONIX 4251-004LF and output filters are TUSONIX 4251-002LF should be used for low RFI applications.

2.9.3 ANALOGUE STEPPER MOTOR DRIVER

Another commercially available low RFI/EMI stepper motor controller is provided by EMSS (Liebenberg, 2021). This analogue system was designed to drive the cryocooler stepper motor for the Band 2 feed of the SKA radio telescope. The controller uses an FPGA to generate two orthogonal sinusoidal signals via DACs, which are digitally filtered on the controller board and routed through filtered connectors to the power amplifiers in the input power cavity (Figure 26).

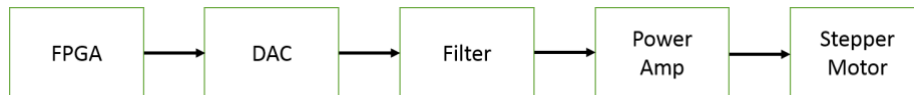


Figure 2.27: FPGA based motor controller (adopted from Liebenberg, 2021).

Motor speed can be adjusted between 45 and 75 rpm by varying the sinusoidal frequency. The analogue motor driver (Figure 27) consists of power rectification and filtering and two power amplifiers, one for each motor coil. Each amplifier is a simplified three-stage audio power amplifier with a differential input stage, voltage amplification stage, and output stage. The input stage uses a 1 mA current source set by specific resistors and a Miller capacitor for stability. The second stage includes a 10 mA current source and a bias spreader transistor

mounted on a heatsink for temperature compensation. The output stage uses pre-driver transistors (MJE243G/MJE253G) and high-power transistors (MJE15032/MJE15033) with negative feedback to control gain, which is set to 28 to accommodate DAC output limitations.

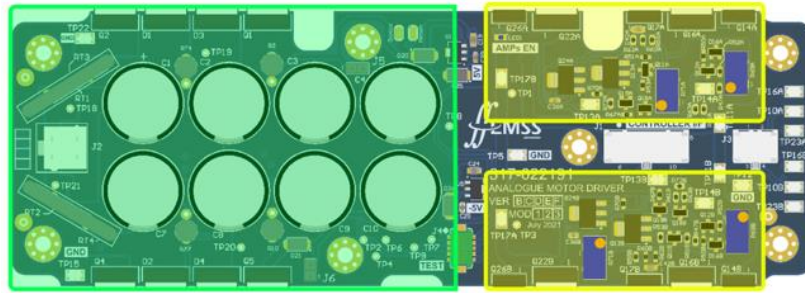


Figure 2.28: Analogue motor driver (adopted from Liebenberg, 2021).

The FPGA-generated sinusoidal signals are first-order RC filtered before being applied to the amplifiers. While this fully analogue design is excellent for reducing EMI, achieving precise position control is more challenging compared to digitally controlled micro stepping approaches.

2.10 MOTOR SIZING & MECHANICAL CONSIDERATIONS

According to (Tang, 2020) determining torque requirements is a important step in selecting a motor, it ensures the motor can handle the intended load and operate optimally. The motor's torque must match or exceed the load's demands to avoid performance issues. Too little torque will prevent effective load movement, while an oversized motor will waste energy. Torque is also crucial during acceleration and deceleration, allowing the motor to start, stop, and change speeds smoothly without overshooting or instability. The maximum static torque a motor can generate, is important for preventing damage during obstructions. Selecting a motor with appropriate torque capacity reduces energy consumption and in turn reduces operating expenses. Torque comprises two main components: load torque and acceleration torque. Load torque involves frictional and gravitational forces necessary to maintain motion, while acceleration torque is the additional torque needed to achieve the desired speed change.

The total torque requirement can be expressed as:

$$\text{Torque} = (\text{Load Moment of Inertia} \times \text{Angular Acceleration}) + \text{Friction Torque}$$

Load torque is described as the torque required to overcome the continuous resistive forces acting on the system, including friction and gravity (Tang, 2020).

Where acceleration torque is required only during periods of acceleration or deceleration, and its magnitude increases with the rate of acceleration. In high-speed or rapid motion profiles, acceleration torque can become a significant contributor to the total torque demand, and both components must be accurately calculated to ensure proper motor sizing.

As illustrated in Figure 2.29 several forces interact in a typical motor-driven application. Load torque is the sum of both frictional and gravitational torques.

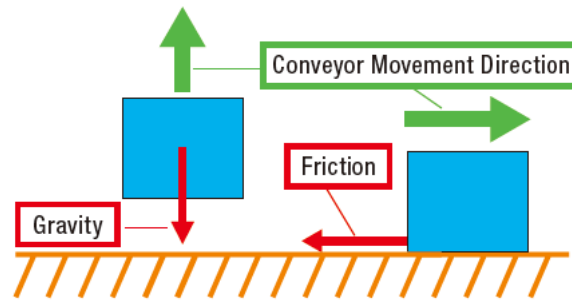


Figure 2.29: Load torque (from Tang, 2020).

The gravitational force is determined by the product of the mass and gravitational acceleration ($F_g = m \times g$), while the frictional force, acting opposite to the direction of motion, is given by ($F_f = m \times \mu$), where μ is the coefficient of friction between the moving surfaces. The method of calculating load torque varies depending on the application. For rotary index tables, Friction occurs primarily at the contact points between the support bearings and the rotating table. The radius (r) in this case is measured from the center of the motor shaft to the bearing contact point, while the mass (m) includes both the table and any mounted loads. The coefficient of friction (μ) is typically specified in the bearing manufacturer's datasheet.

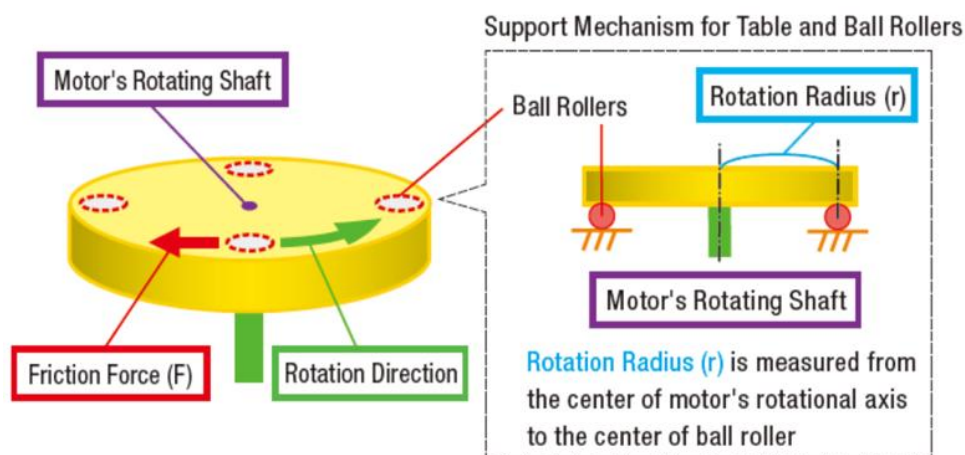


Figure 2.30: Rotary index table (from Tang, 2020).

Accurate calculation of load and acceleration torque is important for reliable performance under all conditions. To assist with this motor selection process, (Oriental Motor, 2022)

provides an online motor sizing calculation tool that simplifies torque estimation, enabling engineers to select a suitably rated motor for their application.

2.11 POWER SUPPLIES FOR RFI QUIET ENVIRONMENT AND TRANSFORMER SELECTION

In applications demanding low EMI the design of the power supply is critical not only for electrical performance but also for EMC. The power supply must deliver stable voltages while minimising conducted or radiated emissions that could increase the EMI from the system.

2.11.1 LINEAR POWER SUPPLIES: ADVANTAGES AND CONSTRAINTS

As detailed by (Hesener, 2010) a low-noise power supply uses a mains transformer for isolation and voltage reduction, followed by rectification and a linear regulator. The regulator uses a transistor in its active region to maintain a precise output, making it quiet in switching noise. However, it dissipates significant power as heat, leading to poor efficiency and thermal challenges. EMI sources, like transformer windings and diodes, can cause magnetic coupling, capacitive noise, and transient issues unless shielded and filtered. Thus, a linear supply design for RFI-quiet applications must integrate filtering and shielding early in the design. A power supply design developed by EMSS Antennas for the MeerKAT L-band receiver (Liebenberg and Marais, 2013) uses linear regulators to minimize electrical noise and ensure stable, low-ripple operation. Custom toroidal transformers is specified to optimize the input voltages supplied to the regulators, all power-dissipating components are mounted on low thermal resistance heatsink blocks to enable efficient heat transfer to the enclosure due to poor thermal performance of linear regulation. The +6 V rail for the FPGA utilizes the LT3080 linear regulator from Linear Technology, housed in a 5-lead TO-220 package to minimize thermal resistance. This device offers several features, including a configurable output voltage, low output noise, foldback current limiting, over-temperature protection, and efficient thermal coupling to the chassis. A +24 V regulator circuit is implemented on the PCB but remains unused, as the stepper motor controller is powered from an unregulated, filtered supply (refer to Section 4.3). The provisional design employs a UC2836 controller with an external TIP36C transistor, and jumper connections are provided to enable this regulator if required in future configurations. Before distribution to system loads, each regulated voltage passes through a multi-stage low-pass filter to suppress residual differential- and common-mode noise. As illustrated in Figure 2.31, the first stage consists of a choke inductor and large bypass capacitors, forming a low-pass section with a cutoff frequency in the kilohertz range, followed

by a second-stage T-type feedthrough filter that provides high-frequency attenuation and includes a common-mode choke to further reduce conducted EMI.

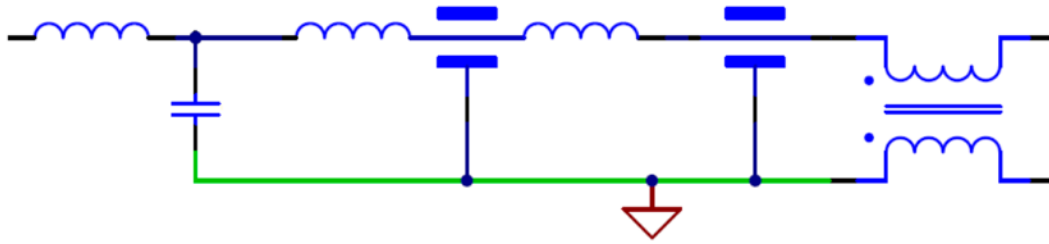


Figure 2.31: PSU output filter Topology (adopted from Liebenberg and Marais, 2013).

2.11.2 SWITCH-MODE POWER SUPPLIES: EFFICIENCY VS EMI CHALLENGE

Switch-mode power supplies (SMPS) have become prevalent in modern systems due to their high efficiency, reduced size, and improved thermal performance (Zhang *et al.*, 2020). By rapidly toggling a transistor between on and off states, they minimize power lost across the switch. However, the fast transitions inherently generate high-frequency harmonics and voltage ringing, which become a significant source of EMI (Hesener, 2010). The challenge is to manage both differential-mode and common-mode noise, especially for compliance with standards such as CISPR 22. According to TI's EMI overview (Hesener, 2010), radiated emission test frequencies often extend up to 1 GHz or more, so suppression strategies must address a wide band. (Hegarty, 2018) Filters for SMPS use multi-stage π (or T) topologies with inductors and capacitors to reduce harmonics without affecting control stability (Zhang *et al.*, 2020).

2.11.3 TRANSFORMER DESIGN FOR EMI-SENSITIVE SYSTEMS

The transformer often causes electromagnetic interference, especially in linear power supplies, so its design must reduce leakage inductance and inter-winding capacitance to lower noise. Using electrostatic or Faraday shields bonded to chassis ground can help divert high-frequency currents, lowering ground loops and noise coupling (Kourtessis, 2019). Toroidal or shielded-core transformers are advantageous because they contain stray magnetic flux, reducing radiated magnetic fields and improving efficiency compared to conventional E-I cores (Talema, 2019). To further reduce the coupling levels between analogue and digital subsystems, separate multi-secondary toroidal transformers can be used, these provide isolation and noise segmentation. Toroidal designs also offer reduced size and weight, lower stray fields, and generally superior thermal performance. In the MeerKAT L-band receiver power supply developed by EMSS Antennas, custom toroidal transformers were specified and manufactured by Toroid

Corporation of Maryland. (Liebenberg and Marais, 2013). Practical implementation of these transformers and linear power supplies is illustrated in Figure 2.32

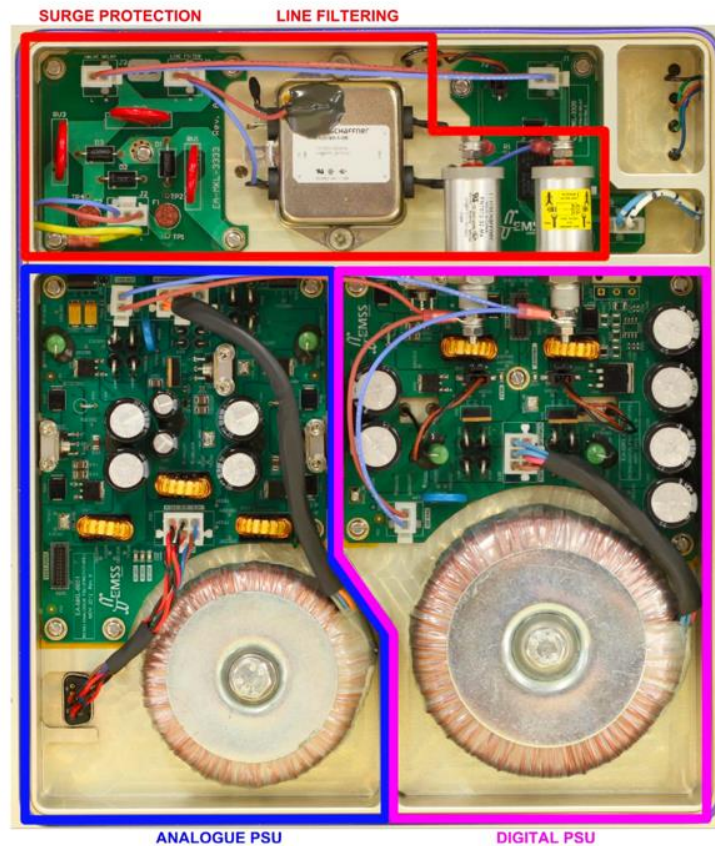


Figure 2.32: Meerkat RCMU power supply implementation (from Liebenberg and Marais, 2013).

2.12 MICROCONTROLLER AND PROGRAMMING

Microcontrollers (MCUs) are compact systems with CPU, memory, and peripherals on one chip, ideal for embedded control needing deterministic timing, low power, and small size. (Patterson & Hennessy, 2017). A practical and common example is the ATmega328P MCU used in Arduino boards (Figure 2.33). This MCU provides a versatile platform for learning and prototyping embedded systems. The ATmega328P integrates a CPU capable of executing instructions efficiently, non-volatile memory (Flash/EEPROM) for program storage, volatile SRAM for runtime data, and multiple I/O interfaces for interacting with sensors, actuators, and communication modules such as UART, SPI, and I²C. MCUs often employ (Barr and Massa, 2006).



Figure 2.33: Arduino ATmega 328p.

The device contains on-chip peripherals that simplifies system design by enabling precise timing with timers and counters, sensor acquisition via ADCs, and PWM outputs (Peatman and John B, 1988) Programming MCUs typically involves languages like C or C++ with IDEs such as Atmel Studio or Arduino IDE for code generation and compiling.

In EMI-sensitive applications, careful MCU design is essential to minimise interference. For instance, selecting an appropriate clock frequency, such as 1 MHz instead of the default 16 MHz on an ATmega328P, will shift digital switching harmonics to lower frequency bands (Ott, 2009). Example of use of low frequency clocks is common where fast operation is not required (Liebenberg and Marais, 2013).

Grounding strategies, including single-point or star-ground layouts, can help prevent ground loops and minimize common-mode currents (Williams, 2007a). Decoupling bypass capacitors, usually 100 nF ceramic with 10 μ F electrolytic near MCU power pins, offer low-impedance paths for high-frequency transients, ensuring stable operation and low emissions.

When these design considerations are implemented, microcontrollers such as the ATmega328P deliver reliable, high-precision control in real-time applications while being able to provide good EMI performance

2.13 COMMUNICATIONS FOR REDUCED EMISSIONS

In EMI-sensitive systems, communication interfaces are often significant sources of conducted and radiated emissions. Traditional UART (Universal Asynchronous Receiver/Transmitter) uses single-ended voltage signals over copper conductors, these are highly susceptible to EMI and can radiate EM (Ott, 2009). Long or unshielded UART cables act as antennas, increasing radiated emissions, while shared system grounds may create ground loops that propagate noise through the communication line (Williams, 2007a; Ott, 2009). Fibre-optic communication solves these issues by transmitting data as light, single-mode fibres provide low attenuation,

high bandwidth, and EMI immunity, ideal for long-distance, high-precision uses like antenna control and sensor data in radio astronomy (Ott, 2009).

Fibre-UART combines the logical simplicity of UART with the EMI immunity of fibre. In this approach, standard UART signalling start bits, stop bits, parity, and baud rate is maintained, but the electrical signals are converted into optical pulses via a UART-to-optical transceiver. At the receiving end, the optical pulses are converted back into standard UART voltage levels, preserving compatibility with microcontrollers such as the ATmega328P while eliminating ground loops and EMI ((Talema, 2019;)&(Kourtessis and Fuse Inc, 2024). This method allows designers to reuse existing UART-based firmware and software while gaining the benefits of fibre-optic transmission, including longer communication distances without additional repeaters or differential signalling.

Table 2.5: Traditional UART vs fibre vs UART.

Feature	Traditional UART	Fibre-UART
Signal Medium	Electrical voltage/current	Light (UART protocol preserved)
EMI Susceptibility	Moderate to high	Negligible
Ground Loops	Possible	None
Distance Capability	Short (<50 m typical)	Long (depends on fibre type)
Bandwidth	Moderate	Moderate (UART baud rate limited)
Isolation Requirement	Opto-isolators recommended	Not required
Complexity & Cost	Low	Moderate

By using fibre or Fibre-UART interfaces, EMI-sensitive systems can achieve reliable data transfer while maintaining low-noise operation. Fibre-UART is particularly useful when microcontrollers such as the ATmega328P must communicate over longer distances or in high-EMI environments while retaining standard UART protocol compatibility.

2.14 DESIGN TECHNIQUES FOR REDUCED EMISSIONS

An article series by Keith Armstrong in the EMC journal summaries partial EMC design aspects to consider when designing for reduced emission. Additionally, practical real-world examples implemented in the design and manufacturing of the SKA and Meerkat receiver systems were also investigated. These techniques are presented summarised below.

2.14.1 CIRCUIT DESIGN AND CHOICE OF COMPONENTS FOR EMC

When designing electronic systems with EMC in mind, the correct choice of active and passive components and circuit design techniques should be used from the start of the research and

development of a design project. Using these techniques will assist with EMC compliance in the most effective manner. It can further reduce the size, weight, and cost of filtering and shielding requirements.

When choosing components for your circuit design, the following aspects recommended by (Armstrong, 2006a) should be considered:

- Use devices with specified EMC features or performance.
- Select components where manufacturers specify reduced emissions.
- Select components where manufacturers specify/mention increased immunity.
- As a general rule, when selecting active devices for analogue circuits, try to choose circuit topologies that are better for EMC and try to keep their dV/dt and dI/dt as low as possible.
- If possible, avoid switch-mode power conversion topologies as they are inherently electrically noisy and produce very high emissions levels if not carefully designed using the EMC techniques.
- The best communication methods for EMC purposes are using infrared, free-space or fibre-optics methods.
- The communication system transmitters must not have excessive emissions, and the receivers should be immune.
- Shielded transmitters and receivers are readily available and are preferred.
- All passive components suffer from parasitic inductance, resistance, and capacitance, also called stray R L C. At high frequencies, this stray RLC should be considered, as this will dominate the impedance of components and has a functional impact on their operation.
- Always consider published data by manufacturers on impedance versus frequency over the design frequency.

2.14.2 SEPARATION OF DIGITAL CIRCUITRY

In high-performance electronic systems, especially those with sensitive analogue or RF signals, separating digital and analogue circuitry is essential to minimise EMI and maintain signal integrity (Liebenberg and Marais, 2013). Digital circuits generate fast-switching currents and voltage transients that can couple into nearby analogue components, causing noise or measurement errors.

Separation is achieved through physical partitioning into distinct cavities, dedicated ground planes, controlled signal routing, and filtered or shielded interfaces. In the receiver control and

monitoring unit (RCMU) of the Meerkat L-band receiver , the FPGA and other digital components are housed separately from the cryostat's analogue circuitry, which supplies RF bias voltages and temperature control. Communication between these subsystems uses filtered pathways or fibre-optic links, preserving both digital command integrity and analogue signal quality. Figure 2.34 & Figure 2.35 illustrates two isolated cavities connected via fibre interfaces.

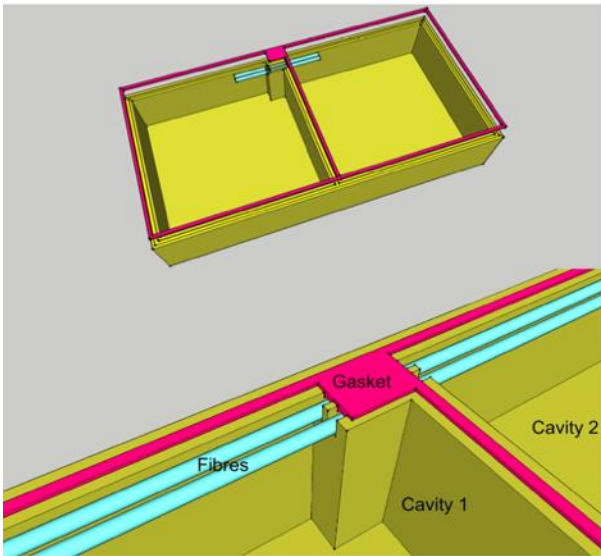


Figure 2.34: Simplified illustration of the fibre feed-through concept (from Liebenberg and Marais, 2013).

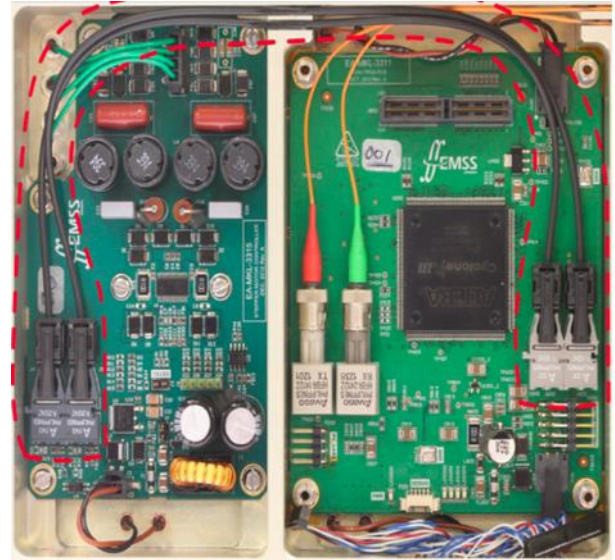


Figure 2.35: Practical implementation of separation of digital circuitry from Liebenberg and Marais, 2013).

2.14.3 CABLES AND CONNECTORS

A common problem in EMC design is the interconnections between circuits inside of a product or between various subsystems. These days the frequencies at which digital electronics operate are so high that all internal conductors can be a significant source of EMC problems unless products have well shielded and filtered enclosure interconnections while minimizing their accidental antenna effects. Some design techniques as presented by (Armstrong, 2006b) to consider for reduced emissions between interconnections are:

- Route conductors with at least one dedicated return conductor/path and keep them as close as possible to each other without compromising insulation.
- When multiple PCB's are used in a design, it should be considered to use flex-rigid PCB's with an overall ground plane for interconnections instead of traditional flexible jumpers, connectors or cables. The benefit is that the 0V plane is continuous over the entire flex-rigid assembly and provides effective shielding.
- Another powerful design tool is segregation. The aim should be to segregate and shield sensitive circuits and products from noisy ones by as much physical distance as possible.
- Earthing and grounding can provide improved EMC performance when a low impedance earth/ground structure is closer to the product to be grounded than a 10th of a wavelength or less.
- Make use of shielded cables and connectors, glands and joints. A 360° coverage shield along the length, including connectors, glands and joints of the cable, is required for good shielding performance.

A practical example of this as presented by (Conradie, van Niekerk and Liebenberg, 2015; Liebenberg, 2021) As shown in Figure 2.36, all external copper harnesses utilise environmentally sealed and EMI-shielded MIL-DTL-38999 connectors. These cables incorporate braided shielding that is terminated with continuous 360° electrical contact to EMI-shielded back shells. Heat-shrink boots and UV- and weather-resistant cable jackets provide additional environmental protection. The fibre interface employs ODC-4 environmentally sealed connectors. According to the manufacturer's datasheet, these connectors feature solid metal-to-metal coupling, grounding fingers, electroless nickel plating, and thicker wall sections, providing an EMI shielding effectiveness of at least 65 dB at 10 GHz, as illustrated in Figure 2.37.



Figure 2.36: EMI rated D38999 connector
(adopted from Liebenberg, 2021).



Figure 2.37: EMI rated ODC-Fibre connector
(adopted from Liebenberg, 2021).

2.14.4 FILTERING AND SHIELDING

Filters are used to attenuate the undesirable signals travelling along conductors. They are categorized by frequency versus attenuation curves. By placing filters on strategic positions, the EMC performance can be increased (Armstrong, 2006c). Filters can be placed at the following positions:

- Inline filters on interconnections between segregated (quiet and noisy) circuits.
- At the interfaces of shielded enclosures.
- Outputs of digital circuits.

Then one of the most effective methods to reduce emissions is by shielding. Shielding is used to attenuate unwanted EMI. Shielding and Filtering need to be used together in order for either one to provide the EMC benefits required (Armstrong, 2006d).

Most shields need to be volumetric and surround the product to be shielded in all three dimensions. For example, a six-face rectangular box can be used to shield a rectangular PCB. This complete volumetric shielding method is also known as a faraday cage. Shielding can also be used inside products to protect sections from EM fields generated by other sections in a product; the same applies to overall enclosure shields. Keith Armstrong in (Armstrong, 2006d) states that for a shielded enclosure to function as intended, they require good electrical contact along all sides, seams, joints or connector interfaces. It is recommended that EMC gaskets are used to prevent apertures along these sides, seams, joints or connector interfaces and also provide RF bonding.

A practical example of this implementation is presented in the design document of the receiver control and monitoring unit of the L-band Receiver for the Meerkat radio telescope (Liebenberg and Marais, 2013). At the interfaces between the enclosure and its lids, high-performance conductive elastomer gaskets are employed to ensure both electrical continuity and environmental sealing. These gaskets are made from a silicone elastomer filled with silver-plated aluminium particles, providing excellent conductivity and mechanical resilience. When

correctly installed, the material achieves a shielding effectiveness greater than 100 dB up to 10 GHz. Conductive gaskets can be produced by die-cutting, injection moulding, vulcanising strips, or formed in place under CNC control allowing adaptation to complex enclosure geometries while ensuring reliable electrical contact refer to Figure 2.34.

Each load circuit within the controller includes a low-pass filter network at the power input stage. This network serves to attenuate both common-mode and differential-mode noise while also providing overvoltage protection, thereby ensuring clean and stable power delivery to the sensitive electronics.

The RCMU enclosure is divided into two main cavities, with the power supply unit (PSU) on one side and the load circuits on the other. These sections share a common conductive wall through which the DC supply voltages both the supply and return lines are routed using discrete feedthrough filters. These filters employ a π -network topology that provides high attenuation across a broad frequency range. Depending on mechanical constraints, they can be bolted into threaded holes or secured with a washer and nut from the rear, Figure 2.38 shows an example of this filter type.

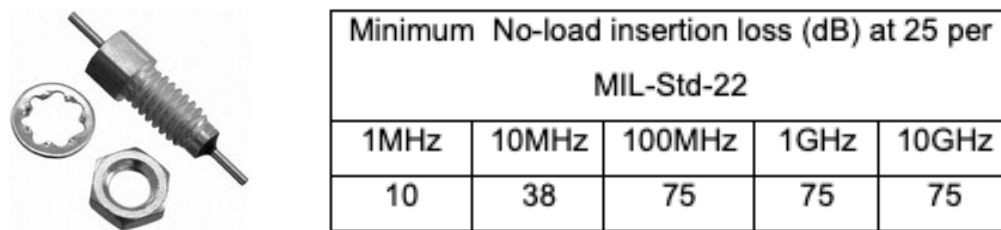


Figure 2.38: Tusonix 4251-004 feedthrough filters (adopted from Liebenberg, 2021).

To further maintain the electromagnetic integrity of the system, low-pass filtered connectors are used wherever signals pass between the RCMU cavities. These connectors suppress high-frequency noise and preserve the overall shielding effectiveness of the enclosure. For this purpose, Spectrum Control Series 700 high-performance filtered connectors are employed for all inter-cavity power and signal links. The connectors are rated for 150 V, 5 A, and incorporate a waved metal gasket between the connector flange and the chassis to ensure a continuous conductive seal. A typical Series 700 D-Sub connector, along with its insertion-loss performance (trace E), is shown in Figure 2.39 & Figure 2.40.



Figure 2.39: Series 700 D-Sub filtered connector (adopted from Liebenberg, 2021).

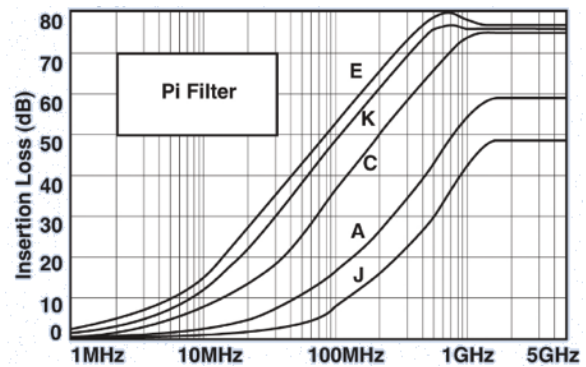


Figure 2.40: Series 700 D-Sub filtered connector IL (adopted from Liebenberg, 2021).

2.14.5 PRINTED CIRCUIT BOARD DESIGN AND LAYOUT

After the component selection techniques have been used to choose components, the next lowest assembly level is the PCB, and most of the EMC issues can be dealt with in the layout of the PCB. The first and most cost-effective technique is segregation, identifying all components that are possibly noisy and quiet components and trying to separate them. For example, try to separate all digital and analogue components from each other. Then various filtering and suppression techniques can be employed between the quiet and noisy circuits (Armstrong, 2006e). The following techniques can also be utilised:

- Power rail decoupling: use decoupling capacitors to provide low impedances at frequencies of concern local too noisy components.
- Decap all IC power pins.
- Terminate all unused IC pins to either the supply or ground.

Another practical example of EMI mitigation is presented by (Liebenberg, 2021) the design of the Feed Package Controller, an FPGA-based PCBA used in the Band 2 Receiver for the Square Kilometre Array. The controller board is housed within a double-cavity enclosure incorporating two RF seals, as illustrated in Figure 2.41.

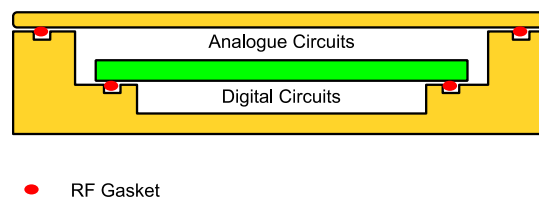


Figure 2.41 Dual RFI shield implementation of the controller board (adopted from Liebenberg, 2021).

All digital circuitry is located on the bottom side of the PCB, while all analogue circuitry is placed on the top side. The six-layer board confines digital signal routing to the bottom four layers using blind vias, with board-level filtering applied at all transitions between the analogue and digital domains (i.e., feedthrough vias).

The first RFI shield is formed by the recess in the enclosure cavity, featuring a groove for the RFI gasket and the PCB assembly itself. During RFI testing, this shield provided an attenuation of approximately 20 dB. The area within the gold border in Figure 2.42 indicates the boundary of the inner cavity, enclosing the critical components.

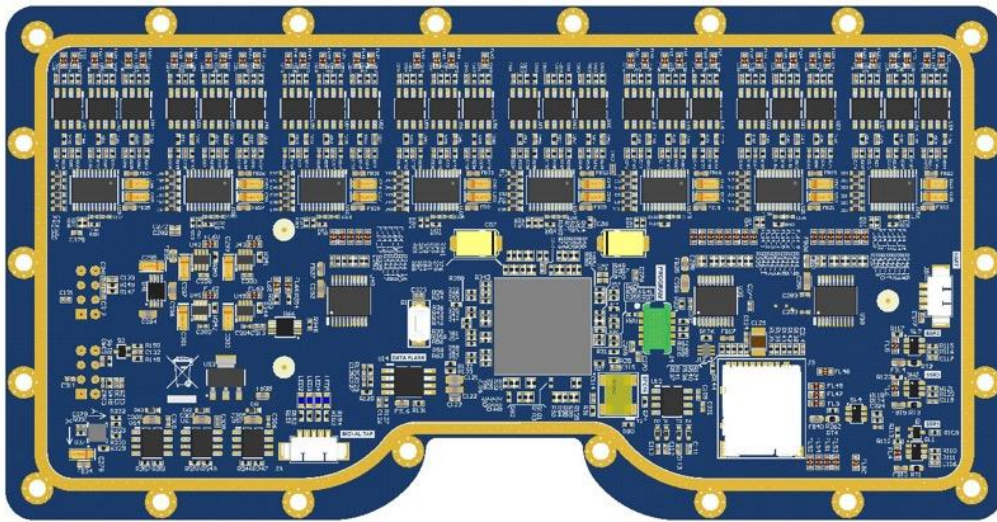


Figure 2.42: Digital circuitry of controller board (bottom side) (adopted from Liebenberg, 2021).

2.14.6 ELECTROMECHANICAL DEVICES

Many typologies of motors and electric generators employ commutators that spark and emit bursts of transient noise at a constant rate. This noise can interfere with other electronic systems and causes EMC problems. The best way to address this problem is to not use electric motors at all, which is not always possible (Armstrong, 2006g). The next best method is to use electric motors that are based on different topologies such as:

- Brushless DC motor
- Stepper
- Switched reluctance motor
- Pancake' or 'PCB' motors

These motor types do not spark and do not create wideband emissions; however, each of these topologies has its own EMC emission problems over limited frequency ranges. They might need some form of EM suppression.

2.15 CONCLUSION

In conclusion, the literature review offers a detailed overview of EMC principles, standards, and design considerations, emphasising EMI sources, coupling mechanisms, and adherence to standards like IEC 61000, CISPR, and MIL-STD-461. It examines EMC testing methods, including pre-compliance techniques, emissions, immunity testing, and antenna standards, to understand interference mitigation. The review emphasises EMI aspects of electric motors, power supply design for RFI-sensitive settings, and emission reduction strategies via circuit design, components, PCB layout, and shielding. It briefly explores microcontroller programming, communication protocols, and device integration, highlighting hardware-software interaction for EMC. This study provides a foundation for future research, offering insights for designing, testing, and optimising low-emission electronic systems in complex environments.

CHAPTER 3 DESIGN REQUIREMENTS

The antenna test turntable was designed to adhere to particular mechanical, electrical, and electromagnetic standards for applications in EMC and antenna test environments. It emphasises portability for easy setup in various locations. It supports up to 25 kg and allows stable, precise rotation from 1° to 360°, with 1° accuracy for accurate angular positioning. Powered by 230 VAC mains using an industry-standard power interface. Communication interface for remote operation is implemented using fibre optic links. One of the main design requirements is to utilise COTS components as much as possible, simplifying development. The applicable operational frequency range of 50 - 1000 MHz covers the bandwidth typical for EMC and antenna characterisation tests, requiring careful attention to shielding, grounding, and cabling practices throughout the design. The applicable radiated emissions limit is CISPR 32 class B. Table 3.1 outlines the requirements in the form of a traceability matrix. The traceability matrix shows how functional, mechanical, and EMC requirements were met through specific subsystem choices and design measures. Using COTS components like EMI-rated filters, optical interfaces, and shielded enclosures helps ensure the turntable's precision and electromagnetic compliance without adding complexity.

Table 3.1: Requirements Traceability Summary Table.

Requirement	Subsystem	Design Implementation	Verification Method
Portability	Mechanical	Lightweight aluminium chassis and detachable base assembly	Physical inspection and weight verification
Load capacity ≥ 25 kg	Mechanical	High-torque NEMA 17 stepper motor with 50:1 gearbox and reinforced bearing assembly	Load test with incremental weights
Rotation angle 1–360°	Mechanical / Control	Micro stepping driver (DRV8818) with home reference switch, stepper motor with fine pitch gearbox	Functional rotation test
Positioning accuracy $\leq 1^\circ$	Control / Mechanical	Closed-loop micro stepping control and fine-pitch gearbox	Angular displacement measurement
Operational frequency range 50 - 1000 MHz	EMC / Electrical	Shielded enclosures and filtered interconnections	Spectrum analysis and EMC/RFI chamber testing
Radiated emission compliance (CISPR 32 / Class B)	EMC	EMI Mitigation design, use of Shielded enclosures and filtered interconnections	Radiated emission testing per CISPR 32

Requirement	Subsystem	Design Implementation	Verification Method
Power supply: 230 VAC	Electrical	IEC-compliant fused power inlet (1.25 A slow-blow ceramic fuse) with LC input filter	Electrical safety inspection and functional test
Remote position control	Control / Interface	Fibre-optic communication link for full galvanic isolation	Command-response verification
Control interface: single-mode fibre optics	Control / EMC	Industrial-grade optical transceivers integrated into MCU control board	Design documentation review
Use of COTS subsystems	System / Design	Selection of commercially available motor, driver, filters, MCU modules, and enclosures.	Design documentation review

CHAPTER 4 DESIGN PHASE

The design phase is central to developing the antenna test turntable (ATT). During this stage, functional requirements are converted into a practical design. The main goal is to ensure the ATT functions effectively within the intended electromagnetic environment of antenna and EMC testing facilities, without causing interference or affecting measurement accuracy.

4.1 SYSTEM ARCHITECTURE FORMULATION AND OVERVIEW

The ATT is designed for environments with strict EMC requirements, where even slight emissions can affect antenna and EMC test outcomes. To meet these standards, the ATT is divided into three main functional subsystems.

- AC mains input power conditioning and linear power supply
- Stepper motor and motor driver
- Analogue interface circuitry and microcontroller

This partitioning strategy not only supports modularity in design and troubleshooting, but also significantly reduces the risk of digital interference by isolating noise-generating circuits from sensitive analogue and communication functions. Figure 4.1 displays a high-level block diagram of the ATT system. It shows all the shielded enclosures, filtered interfaces, and communication lines. The following subsections provide further details on the techniques used to create a design with lower emissions.

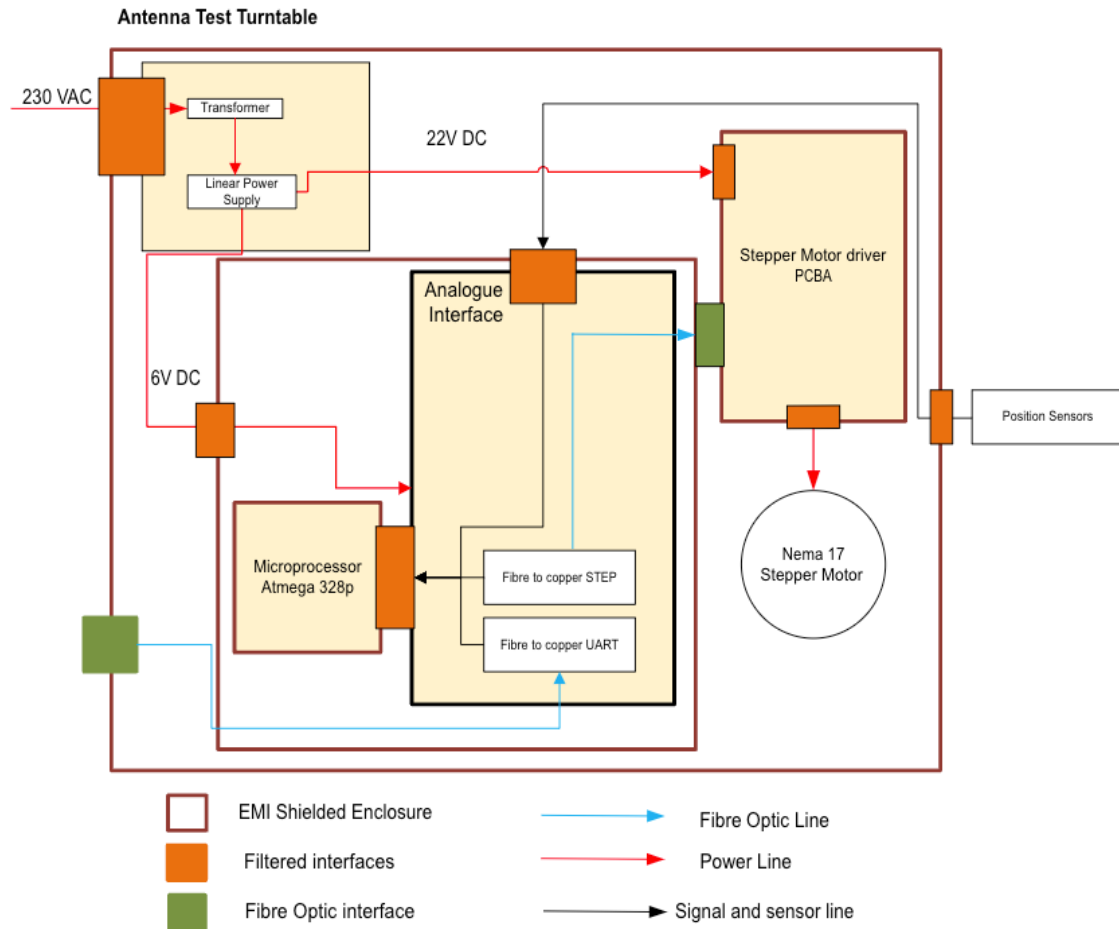


Figure 4.1: High-level block diagram.

4.1.1 PREVENTING DIGITAL INTERFERENCE

Because of the strict EMC standards for antenna measurement setups, it's essential that the ATT does not emit EMI that could be picked up by measurement devices or pollute the test chamber. To achieve this, the following design measures were put in place.

- Multiple levels of low-pass filtering between the digital circuitry and all interface connections.
- Enclosure of the digital circuitry within multi-layer RFI shielding.
- Use of a linear power supply instead of a switching supply to suppress high-frequency noise.

These measures together lower both conducted and radiated emissions.

4.1.2 ISOLATION OF CIRCUITS & SHIELDED ENCLOSURES

The ATT subsystems are arranged in separate shielded cavities to prevent interference from circuits with high switching currents, such as motor drivers, from affecting digital subsystems (MCUs). Where communication between cavities is necessary, optical fibre links are used to avoid galvanic coupling. To ensure high levels off shielding, all signal passthroughs employ

filtered connectors. Custom enclosures would offer better shielding, budget limitations led to the selection of COTS enclosures. To address this, careful layout and additional shielding materials used on interfaces and lids.

4.1.3 FIBRE OPTIC INTERFACE

All external communication with the ATT is implemented via optical fibre shown in Figure 4.2, which provides galvanic isolation and prevents conducted EMI from escaping the enclosure.

- A UART-over-fibre link provides communication with the host PC.
- The interface uses the ODC-4 outdoor connector system (Amphenol AARC. 2005), chosen for its rugged EMI-rated design.

Although the connectors are rated for EMI protection, the main shielding remains the internal cavity enclosures of the ATT, ensuring maximum suppression of interference.



Figure 4.2: External fibre optic interface.

4.1.4 MINIMISE CLOCK FREQUENCIES

To further reduce emissions, the ATT's microcontroller is clocked at only 2 MHz using an external clock reference (see Section 4.3). This relatively low operating frequency ensures that any harmonics fall well below the bands of interest in EMC and antenna testing, thereby reducing the risk of contaminating the measurement environment.

4.1.5 GROUNDING ARCHITECTURE

All digital circuits use a single-point grounding strategy. The only direct DC connection to chassis ground is established at the power supply unit (PSU). From there, power is distributed to the microcontroller and stepper motor controller.

Within each subsystem cavity, Circuit grounds are kept separate from chassis ground, reducing the risk of noisy digital return currents contaminating sensitive analogue paths.

4.1.6 FILTERED CONNECTORS & FILTERS AT POWER INTERFACES

Each subsystem incorporates low-pass filter networks at its power input stage to attenuate both common-mode and differential-mode noise. For additional suppression and system reliability,

multiple levels of filtering are employed. The DC supply lines are fed through Tusonix 4251-004 feedthrough filters (Figure 4.3), which utilize a π -network configuration to provide high attenuation across a broad frequency range. To maintain the EMI shielding effectiveness of the enclosure, filtered D-sub connectors from the Spectrum Control Series 700 (Figure 4.4) range are used for all signals entering or exiting the microcontroller cavity .



Figure 4.3: In-line feedthrough filters.



Figure 4.4: Series 700 high-performance filtered connectors.

These high-performance connectors are available in either π or C circuit configurations, both offering strong attenuation over a wide bandwidth. The π configuration is selected for this design due to its superior suppression of low-frequency interference. Although π circuits can exhibit ringing in switching applications, this is not a concern here. The stepper motor driver outputs are routed through filtered feedthroughs to prevent PWM switching noise from escaping the motor driver cavity(enclosure). This ensures that any high-frequency components generated by the driver's dual H-bridge circuitry remain confined within the shielded motor compartment. Separating filtering and shielding functions in the design enables a cost-effective and robust EMI containment strategy and allows the use of readily available filtered connector types while ensuring high attenuation.

4.1.7 POWER SUPPLY DESIGN

The detailed design considerations for the power supply are elaborated in section 4.3.3 Several measures have been taken to minimise EMI related to the power supply. A linear power supply is used instead of a switch mode power supply, which helps reduce high-frequency noise generated inside the PSU enclosure and possible switching noise on the DC supply lines. A toroidal transformer is selected to minimise stray magnetic fields that could induce noise. Additionally, after regulation, all DC supply voltages go through low-pass filter networks on the PSU circuit board.

4.2 MECHANICAL DESIGN

The mechanical design emphasises the structural and functional aspects of the turntable assembly. It considers load capacity, rotational precision, and the integration of shielding enclosures. Material selection, bearing systems, and housing arrangements are also prioritised for cost-effectiveness and commercial availability. The ATT's mechanical design aims for a compact, stable, and electromagnetically quiet structure capable of precise positioning. A flat-top turntable configuration, as shown in Figure 4.5 was chosen, where the rotating platform mounts directly onto the external housing. This setup eliminates complex coupling parts and simplifies the mechanical connection between the drive system and the platform. It also improves stability as the centre of gravity is lower.

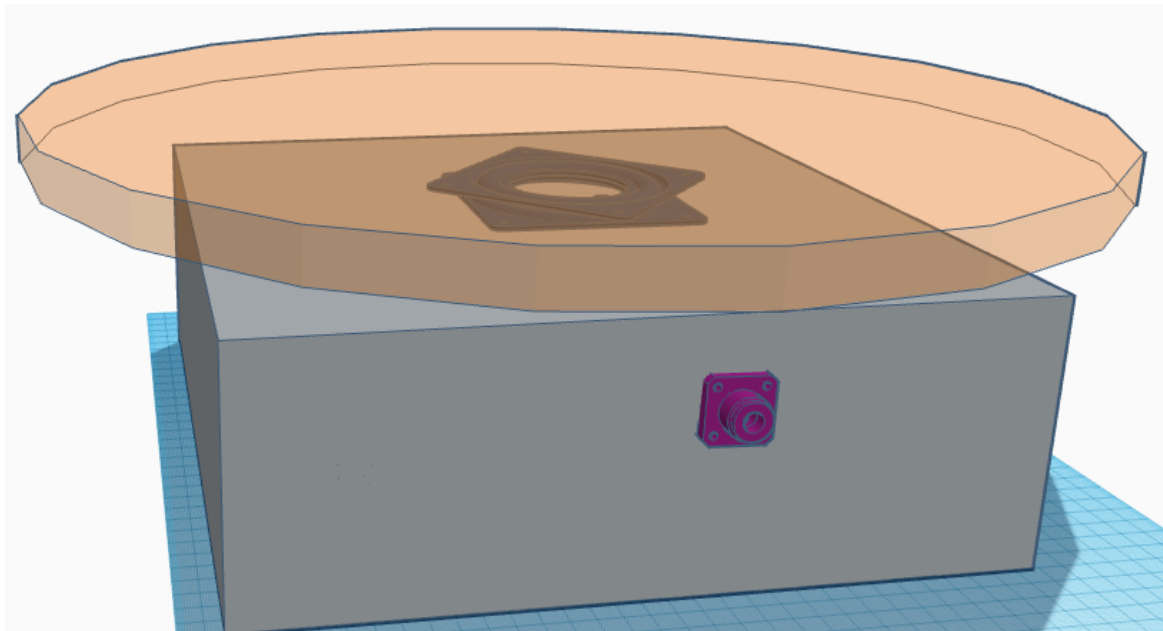


Figure 4.5: ATT flattop design concept.

4.2.1 ROTATING PLATFORM

The rotating platform is supported by a zinc-plated steel 100 mm swivel plate Lazy Susan bearing, shown in Figure 4.6 (PN: LAZYSUSAN 4C), sourced from Bearings Online SA (Bearingsonlinesa.co.za, 2025)

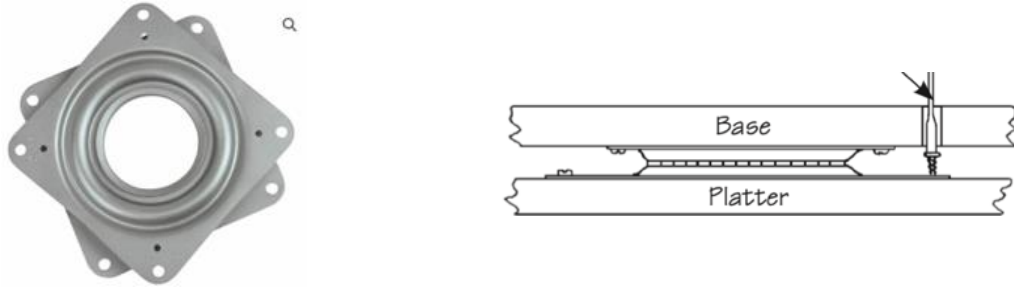


Figure 4.6: Lazy Suzan bearing and tabletop mounting.

The bearing has a load capacity of 136 kg, far exceeding the turntable’s design requirement of 25 kg. It provides a budget-friendly solution that allows smooth rotation while reliably supporting the full axial load of both the table and the test article.

The platform itself measures 300 mm in diameter and is 20 mm thick. It is made from medium-density fibreboard (MDF), chosen for its positive electromagnetic and mechanical properties. MDF’s non-conductive quality and high electrical resistivity prevent eddy currents when exposed to radiated fields, avoiding secondary magnetic coupling and unwanted reflections. Aside from its EMI advantages, MDF offers excellent dimensional stability, is lightweight, and easy to machine. Its dense and uniform structure distributes loads evenly across the bearing assembly. These features collectively make MDF an cost effective and suitable choice for balancing mechanical performance with electromagnetic transparency.

4.2.2 MOTOR SIZING AND TORQUE REQUIREMENTS

A simplified torque model from (Tang, 2020) was employed to calculate the necessary motor torque, factors like friction, load inertia, and system efficiency were considered. The following assumptions were made:

Coefficient of friction between the turntable and support mechanism (bearing): $\mu = 0.1$

- Overall system efficiency: $\eta = 80\%$
- Motor rotational speed: **2 rpm**
- Total load mass: **25 kg**

The load torque (T_l) was computed based on frictional resistance and load inertia, using the methodology from (Oriental Motor, 2022) the resulting parameters are summarised below:

Table 4.1: Motor sizing.

Parameter	Symbol	Value	Units
Rotational speed	ω	2	rpm
Angular range	—	-20° to $+380^\circ$	$^\circ$
Required stopping accuracy	—	0.5	$^\circ$
Load mass	m	25	kg
Load inertia	J	0.7716	$\text{kg}\cdot\text{m}^2$
Acceleration torque	T_a	0.3232	$\text{N}\cdot\text{m}$

Parameter	Symbol	Value	Units
Load torque	T_l	0.3430	N·m
Safety factor	SF	2	–
Total required torque	T_t	1.332	N·m

This calculated total torque ensures sufficient margin to accommodate system losses, mechanical imperfections, and dynamic loads during acceleration and deceleration.

4.2.3 MOTOR AND GEARBOX SELECTION

For this design, various stepper motors were considered, a NEMA 17 stepper motor ($L = 39$ mm) paired with a 50: 1 high- precision planetary gearbox from Stepper Online (PN: 17 HS 15- 1684 S- HG 50) was selected, based on the required torque and desired rotational speed and positional accuracy. The motor (shown in Figure 4.7) delivers up to 10 N·m of torque, far exceeding the necessary amount and enabling smooth, controlled movement at low speeds. The planetary gearbox improves angular accuracy and load capacity and minimises backlash. The bipolar stepper motor features a 1.8° step angle, effectively reduced to 0.036° per step by the gear reduction.



Figure 4.7: Stepper Online Nema 17 stepper motor.

These motors are readily available, cost-effective, and capable of delivering high torque at low speeds without closed- loop systems. Their bipolar design makes integration with standard stepper drivers straightforward. This combination of specifications makes the NEMA 17 stepper motor ideal for the antenna test turntable. The electrical and mechanical specifications are outlined in Table 4.2 &

Table 4.3 adopted from (Stepper Online, 2025)). With a rated phase current of 1.68 A and phase resistance of 1.65Ω , the motor is compatible with common bipolar drivers such as the A4988 or DRV 8825. Mechanically, the gearbox offers 85% efficiency and low backlash (≤ 5 arcmin), providing high positional accuracy. The motor's maximum torque of 10 N·m provides a sufficient safety margin over the calculated 1.332 N·m. Additional ratings include a dynamic axial load capacity of 50 N and radial capacity of 100 N at a 20 mm shaft length, supporting robust performance. The system's rated time between failures (TMBF) exceeds 6000 hours,

ensuring long- term reliability. Overall, this motor- and-gearbox assembly offers a durable, precise, and cost- effective actuation solution for the automated antenna test turntable

Table 4.2: Stepper motor electrical specifications.

Electrical Specification	Value
Manufacturer Part Number	17HS15-1684S-HG50
Motor Type	Bipolar Stepper
Step Angle	0.036°
Holding Torque (without Gearbox)	39 N·cm (55 oz·in)
Rated Current per Phase	1.68 A
Phase Resistance	1.65 Ω
Inductance	3.2 mH $\pm$ 20% (1 kHz)
Insulation Class	B (130°C / 266°F)

Table 4.3: Gearbox specifications.

Specification	Value
Gearbox Type	Planetary
Gear Ratio	50:1
Efficiency	85%
Backlash at No-load	≤ 5 Arcmin
Max. Permissible Torque	10 Nm (1416.4 oz·in)
Moment Permissible Torque	15 Nm (2124 oz·in)
Max. Radial Load	100 N
Ambient Temperature Range	-10°C to 90°C
Noise Level	≤ 50 dB
Life Expectancy	20 000 hours

4.2.4 ENCLOSURE AND PHYSICAL LAYOUT

Integrating the drive and control electronics mechanically posed a major design challenge because creating a single custom enclosure with dedicated internal cavities would have been too costly. To overcome this, a modular enclosure approach was used, utilising commercial shielded aluminium housings to separate the functional subsystems- such as the motor controller, analogue interface, microcontroller, and main power supply- each within its own conductive cavity, as shown in Figure 4.8 & Figure 4.9. The enclosures for each module were chosen to provide effective EMI shielding. The microcontroller housing features a conductive elastomer gasket at lid interfaces to guarantee continuous electrical contact and effective EMI sealing. On enclosures where gasket grooves are absent, as a precaution aluminum tape is applied along enclosure seams to maintain shielding integrity. All interconnections between subsystems are achieved using fibre optics or routed through filtered feedthrough connectors,

incorporating low pass π -filters to reduce both conducted and radiated emissions across inter-enclosure interfaces.

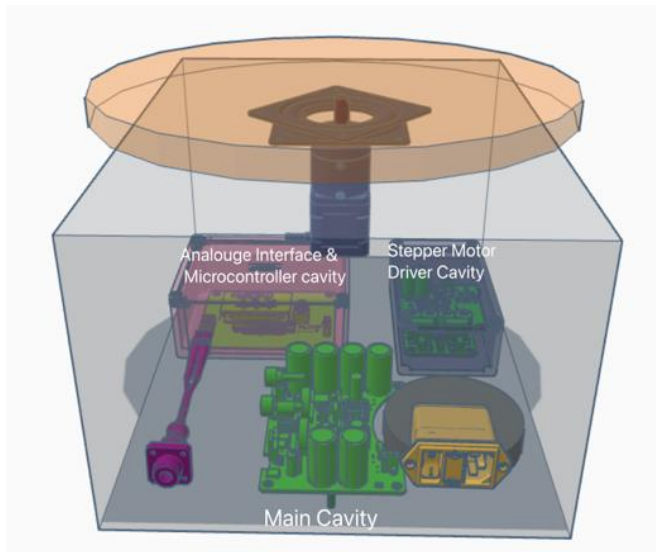


Figure 4.8: CAD design of enclosure layout.

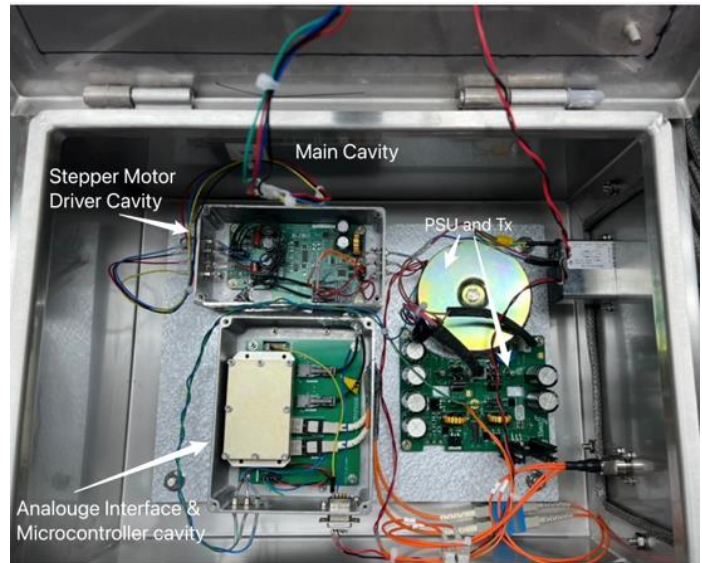


Figure 4.9: Sub-system enclosure implementation.

The main system enclosure selected for the assembly is a 316 stainless steel electrical housing from Enclosure Solutions (Part Number: ENCME3162G)(enclosuresolutions.co.za, 2025) see Figure 4.10, originally designed for industrial outdoor applications and rated IP66 for protection against dust and moisture ingress. The enclosure was selected for its internal dimensions, providing space for all subsystems, and its mechanical robustness, meeting load-bearing and stability requirements of the ATT. These features make it ideal for ensuring both mechanical stability and effective electromagnetic containment within the ATT system. To improve EMC, the standard environmental gasket was replaced with a twin round and fin knitted wire mesh EMI shielding gasket from TE Connectivity (2025), as shown in Figure 4.11. This upgrade helps the housing maintain efficient shielding against radiated emissions.



Figure 4.10: Main enclosure.

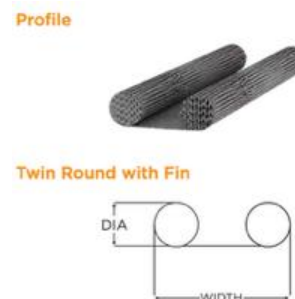


Figure 4.11: Knitted wire mesh EMI gasket.

The enclosure's removable panels greatly simplified machining for power, signal, and fibre-optic interfaces, while the inclusion of an internal mounting plate allowed efficient subsystem assembly and reliable mechanical integration. This modular and shielded configuration shown in Figure 4.12 & Figure 4.13 not only reduced manufacturing costs but also enhanced serviceability, electromagnetic isolation, and mechanical robustness of the antenna test turntable electronics.

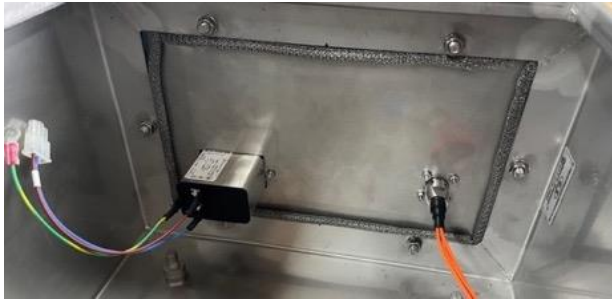


Figure 4.12: EMI Wire mesh shielded panels.

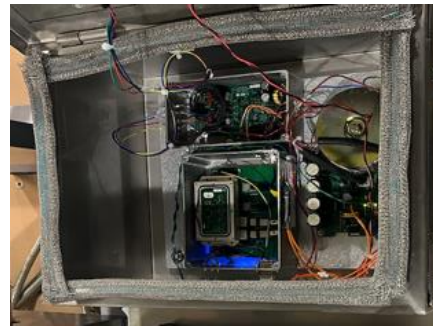


Figure 4.13: EMI wire mesh shielded lid.

4.3 ELECTRONICS DESIGN

The electronics design includes creating the power supply, motor driver circuits, and a microcontroller-based control system. Special focus is given to minimising conducted and radiated emissions to meet EMC standards. Electrical isolation is applied to subsystems when needed, and multi-stage filtering techniques are used. This section also covers grounding strategies, interface design, and fibre optic communication integration.

4.3.1 MICROCONTROLLER SELECTION

The microcontroller module shown in Figure 4.14, originally designed for helium compressor control in the MeerKAT and SKA radio telescopes, was chosen as the processing unit for the ATT. The Helium Compressor Processor (EA- MK- 577), available from EMSS, is based on Atmel's Atmega 328P 8-bit microcontroller. This low- RFI/EMI module uses an external 2 MHz resonator to ensure stable timing and significantly reduce harmonic emissions compared to higher- frequency oscillators. The processor is housed in a machined aluminium enclosure with RFI shielding, surface- treated to prevent oxidation, and sealed with a CHO- SEAL solid O- ring gasket (PN 10- 04- 2657- 1285). This enclosure provides excellent electrical continuity and shielding effectiveness across mating surfaces. Subsystem connections are made through a 25- pin D- sub π - filter connector (Spectrum Control part number 56- 721- 005), which provides attenuation up to 75 dB at 1 GHz. Firmware updates and maintenance are supported via direct in- system programming using the Tag- Connect TC 2030 interface, which allows updates by opening the enclosure.

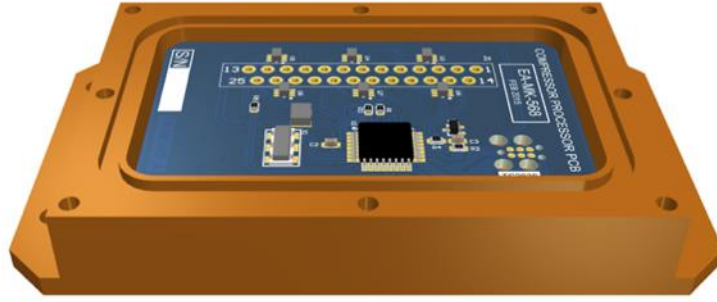


Figure 4.14: Processor PCBA and shielded enclosure.

In the ATT, the microcontroller performs core functions such as:

- UART communication at 4800 baud.
- Stepper motor enable and direction control.
- step pulse generation (PWM).
- monitoring of the position sensor input.

The module's pinout, shown in Appendix A, was used as the basis for firmware development (see section 4.4) and for the analogue interface PCBA design.

4.3.1.1 EMI SOURCES FROM MICROCONTROLLER

The microcontroller subsystem in the ATT presents potential EMI risks due to high-frequency harmonics generated by clock oscillations, fast GPIO switching, and digital signal transitions. These emissions can propagate through output power and signal lines, potentially coupling into sensitive analogue circuitry or the stepper motor driver. To mitigate conducted emissions, a Spectrum Control 56-721-005 π -filter is applied at the output of the microcontroller cavity. Additionally the microcontroller is double shielded and filtered, first inside the microcontroller cavity, then inside the analogue interface cavity as presented in Figure 4.15.

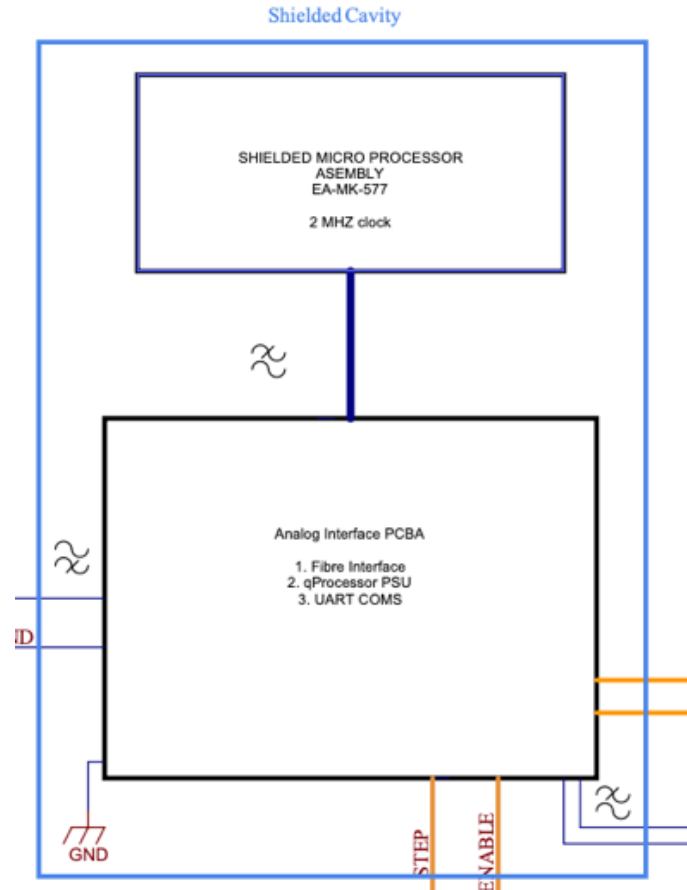


Figure 4.15: Microcontroller shielding and filtering.

The chosen microcontroller offers advantages including reduced EMI. Operating with a low 2 MHz resonator frequency, the 8-bit controller produces less harmonic content than typical high-speed digital controllers. Its slower I/O transition rates also help suppress high-frequency spectral components that might couple into other circuits or radiate through connected cables. Encapsulated within a machined aluminium RFI-shielded housing, residual emissions are contained effectively, and all external connections are filtered through D-sub connectors that ensure up to 75 dB attenuation at 1 GHz.

4.3.2 SELECTION STEPPER MOTOR DRIVER

A COTS low-RFI/EMI stepper motor controller shown in Figure 4.16, available from EMSS, was selected for the ATT. The controller supports low-RFI operation through the use of input and output filters, installation in an RFI-shielded enclosure, and fibre-optic control interfaces. The fibre interface employs the Versatile Link series from Broadcom (Avago)(Liebenberg and van Staden, 2018).



Figure 4.16: COTS low EMI stepper motor driver.

Motor speed is determined by the pulse frequency applied to the STEP input via the J4 fibre interface, or alternatively by an onboard 555-timer oscillator as shown in Figure 4.17.

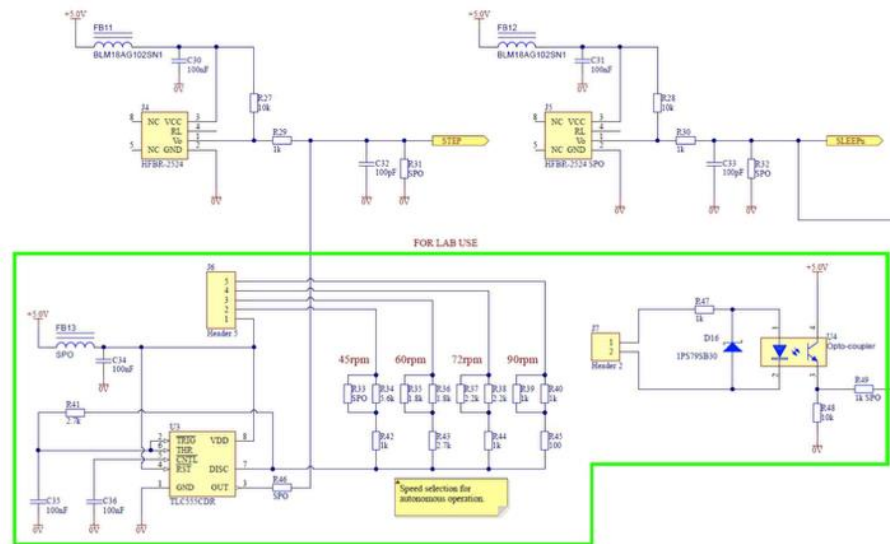


Figure 4.17: Stepper motor speed control (Liebenberg and van Staden, 2018).

Details regarding the stepper motor design is summarised below as obtained from (Liebenberg and Marais, 2013)

4.3.2.1 STEPPER MOTOR DRIVER IC

The stepper controller is based on the DRV8818 dual H-bridge stepper motor driver IC from Texas Instruments. It supports up to 2.5 A per phase and features low output resistance (0.37Ω), resulting in reduced thermal losses compared to similar drivers. The DRV8818 integrates a micro stepping indexer with up to 1/8-step resolution, producing discrete approximations to sinusoidal current waveforms. Each STEP pulse advances the internal current reference table, with closed-loop control maintained by PWM current regulation through winding sense resistors.

4.3.2.2 LOW-PASS FILTERING AND TRANSIENT SUPPRESSION

To reduce high-frequency noise while maintaining proper current regulation, an LC low-pass filter is employed. Shunt capacitance alone would disrupt the PWM control loop and introduce excessive ripple currents. The inductors replace part of the motor's inherent inductance, thereby controlling current rise times and enabling filtered connectors at the output. To suppress voltage transients from the driver's fast switching edges, RC snubber networks are installed across (shown in Figure 4.18) the DRV8818 output pins, positioned immediately before the LC filter. This recommendation follows guidance from Texas Instruments application engineers

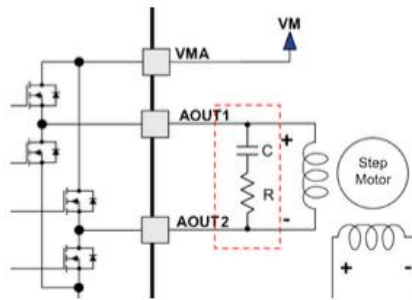


Figure 4.18: Transient suppression RC snubber network.

4.3.2.3 STEPPER MOTOR VOLTAGE REGULATION AND CONTROL SIGNALS

The DRV8818 operates from two voltage domains:

- VM (Motor supply): 24–30 V DC (unregulated, filtered)
- VCC (Logic supply): 5 V DC

The 5 V logic supply is generated by a TL720M05-Q1 linear regulator shown in Figure 4.19. With a maximum current draw of 4 mA, power dissipation is under 100 mW. The regulator's thermal tab connects to the ground plane for efficient heat transfer to the chassis.

Supply lines from the PSU are feed-through filtered and further decoupled on the PCB using local chokes and capacitors to localise switching transients.

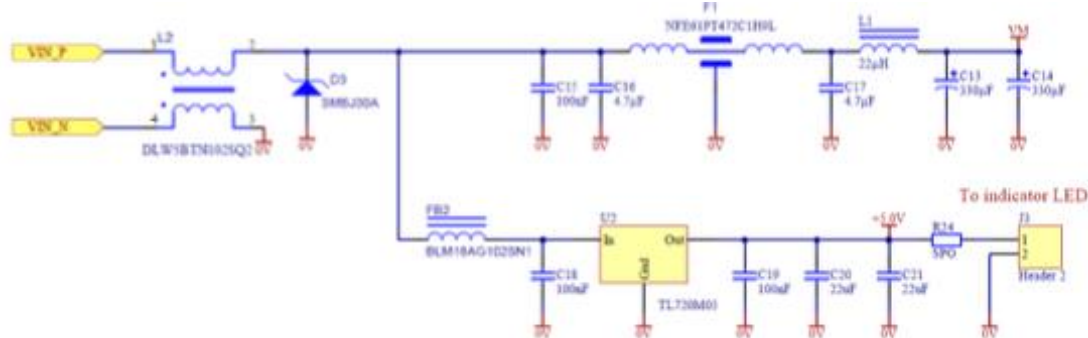


Figure 4.19: Stepper motor PSU.

Control signals from the microcontroller are transmitted via the Versatile Link fibre interface, including:

- **STEP**- Controls rotational speed.
- **nSLEEP**- Disables outputs and enters low-power mode.

Direction control, is provided via a filtered connector.

Although efficient, the DRV8818 requires heat sinking to maintain junction temperatures within specification. The exposed thermal pad on the device is soldered to a large ground plane with multiple vias connecting six copper layers. Heat is transferred through an electrically isolating, thermally conductive Sil-Pad K10 interface to the enclosure for conduction cooling

4.3.2.4 EMI SOURCES FROM THE STEPPER MOTOR DRIVER

Its fast PWM switching controls current through the motor windings with rise and fall times on the order of tens of nanoseconds, generating high-frequency voltage and current transients. These transients produce harmonics extending into the tens and hundreds of megahertz, which can propagate through both power and signal lines. Additional EMI arises from the interaction between the driver and the stepper motor's inductive windings, where rapid current changes induce voltage spikes and ringing. To reduce conducted emissions, filters were installed in the stepper motor cavity, following recommendations from (Liebenberg and van Staden, 2018) the TUSONIX 4251-004LF input filter and the TUSONIX 4251-002LF output filter. The cutoff frequency of a single-stage LC filter was calculated as:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (4.1)$$

Input Filter (4251-004LF):

- $L = 1.5 \text{ mH}$, $C = 4.7 \text{ nF}$

$$f_c \approx 59.8 \text{ kHz}$$

The cutoff frequency is significantly higher than the stepper motor's fundamental frequency ($\sim 0.033 \text{ Hz}$) but lower than the first microcontroller harmonics ($\sim 2 \text{ MHz}$). This effectively reduces high-frequency EMI without affecting normal motor operation.

Output Filter (4251-002LF):

- $L = 0.33 \text{ mH}$, $C = 2.2 \text{ nF}$

$$f_c \approx 187 \text{ kHz}$$

The output filter cutoff is set above the PWM fundamental frequency (~20–50 kHz) but below higher-order harmonics in the MHz range. This configuration enables the filter to smooth the PWM waveform, reduce EMI, and maintain microstepping precision. The use of input/output filtering, RFI shielding, and fibre-optic isolation ensures the stepper motor driver operates with minimal EMI. Filters are selected carefully to allow normal motor function while significantly reducing high-frequency noise, supporting the ATT system’s low-EMI goals and protecting sensitive antenna measurements. The EMSS DRV8818 stepper motor driver provides accurate, low-noise, and reliable performance for the NEMA 17 motor, integrating microstepping, RFI shielding, fibre-optic control, and LC/RC filtering to satisfy all mechanical, electrical, and EMI standards for the ATT.

4.3.3 POWER SUPPLY UNIT

The PSU converts the 230 VAC mains input into regulated DC voltages. It is housed within the main cavity of the ATT. The system’s

4.3.3.1 POWER BUDGET

Table 4.4 lists the power requirements for the ATT on which the PSU design and selection were based. The values shown are a conservative yet realistic estimate of the total power consumption, based on the information available at the time of design.

Table 4.4: Power budget.

Circuit	Supply Voltage	Current	Power
Microcontroller	6V	0.30 A	1.8W
Analogue interface	6V	0.4 A	2.4 W
Stepper motor	24 V-30 V	1.25	30 W

4.3.3.2 POWER LINE FILTER

An IEC C14 filtered inlet module (Schurter DD12.1111.111, 1 A)(Schurter, 2025) with integrated fuse holder was selected. The built-in π -filter (2×10 mH, 2.2 nF) provides approximately 50 dB attenuation between 1 MHz and 100 MHz.



Figure 4.20: IEC power line filter.

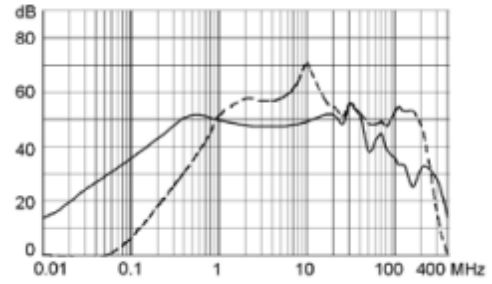


Figure 4.21: Filter insertion loss.

The π -filter cutoff frequency is calculated as:

$$f_c = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(10 \times 10^{-3})(2.2 \times 10^{-9})}} \approx 34 \text{ kHz} \quad (4.2)$$

This cutoff is well below the dominant EMI frequencies of both the 2 MHz microcontroller and the high-frequency PWM from the stepper driver.

The π -filter cutoff frequency of approximately 34 kHz is well below the dominant EMI frequencies generated by both the microcontroller and the stepper motor driver. With approximately 50 dB of attenuation across the 1–100 MHz range, the filter effectively suppresses both conducted and high-frequency harmonic noise. This ensures low-noise operation of the ATT and contains emissions inside of the main enclosure. In addition, the filtered inlet module meets all other electrical and safety requirements with its IEC rating and a 1.25 A slow-blow ceramic fuse implemented to protect the system against overcurrent conditions and enhance operational safety.

4.3.3.3 TRANSFORMER

A toroidal transformer was chosen for the ATT power supply because of its benefits over traditional E-I core transformers. These benefits include smaller size and weight, reduced stray magnetic fields, higher efficiency, less internal heating, and a lower profile (Liebenberg and Marais, 2013). Based on the power needs outlined in Table 4.4, a custom-wound toroidal transformer was built by Toroid Corporation of Maryland, they offer custom transformers as a commercial offering. This customised design optimises the secondary voltages delivered to the regulator and filter circuits, reducing heat generation in the power supply and enhancing system reliability. Figure 22 shows the toroidal transformer, while Table 5 details its specifications from the manufacturer.



Figure 4.22: Toroidal transformer example.

Table 4.5: Selected transformer specifications.

Specification	Value
Circuit	Digital
Part Number	1148
Nominal Supply	230 VAC / 50 Hz
Rated Primary Current	0.23 A
Secondary 1 Output	22 V RMS @ 1.75 A RMS
Secondary 2 Output	8 V RMS @ 1.25 A RMS
Secondary 3 Output	—
Temperature Rise at Rated Load	10°C
Outer Diameter (Max)	100 mm
Height (Max)	41 mm
Weight	1.2 kg
Insulation Class	B (130°C)

4.3.3.4 PSU PCBA

A COTS linear power supply PCBA from EMSS was selected for the ATT . it makes use of linear regulators which delivers low-noise performance. All power components offer the option to be mounted on heatsinks with low thermal resistance, ensuring effective heat dissipation and consistent reliability. The PCBA offers the following core functions:

6 V Regulator for Microcontroller

The microcontroller supply is provided by an LT3080 linear regulator from Linear Technology, chosen to minimise thermal resistance to the enclosure and maintain low output noise. Key features of the LT3080 include:

- Configurable output voltage
- Low output noise
- Current limiting with foldback
- Over-temperature protection
- Low thermal resistance to the chassis

Regulator for Stepper Motor Driver

A regulator circuit for the stepper motor driver is implemented on the PCB but is not used in normal operation, as the stepper driver receives an unregulated, filtered supply voltage. The circuit can optionally be enabled using jumpers and is designed around the UC2836 with an external TIP36C.

Soft Start

All output channels include soft-start functionality. This is implemented with a discrete circuit using pre-set differentiating feedback on the MOSFET gate, which is enabled after inrush limiting has expired. Start-up typically occurs in under 1 ms, while inrush currents last for multiple rectifier cycles. The voltage rise rate is controlled at approximately 0.4 V/ms, preventing large inrush currents to downstream loads regardless of load impedance.

Low-Pass Filtering

Before being distributed to load circuits, supply voltages go through low-pass filters that reduce residual differential and common-mode noise. The initial stage of the differential filter consists of a large choke inductor and a high-capacitance bank, setting a cut-off frequency in the kHz range. This is followed by a second stage with feed-through T-filters and a common-mode choke, which effectively attenuates high-frequency noise and ensures a clean, stable supply for all connected subsystems.

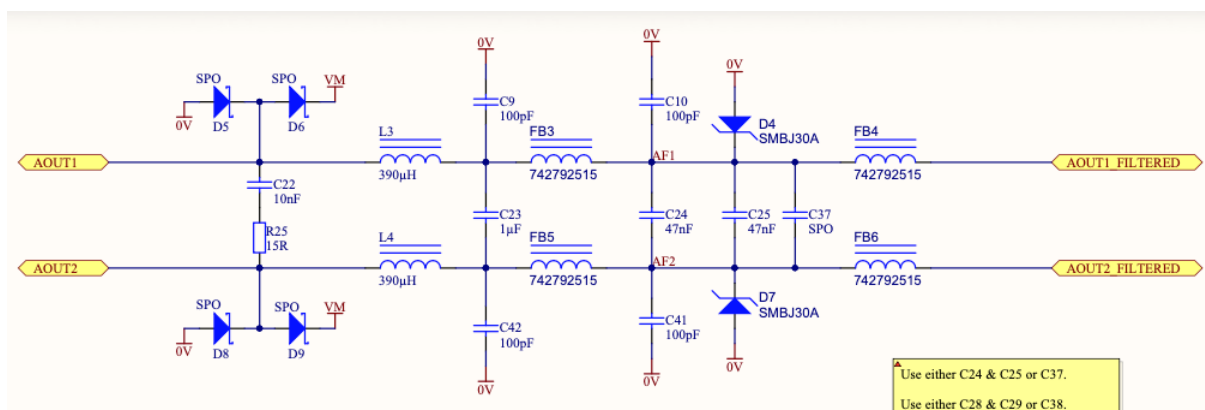


Figure 4.23: Example of output filter implementation.

4.3.4 ANALOGUE INTERFACE

The Analogue Interface (AI) PCBA is a specially designed board that enables integration among the different subsystems of the ATT. It serves as the central interface through which power, control, and communication signals are distributed. To maintain electromagnetic integrity, the AI is housed within a dedicated RFI-shielded enclosure as shown in Figure 4.24, ensuring that noise generated by digital or motor drive circuits does not couple into sensitive analogue or communication lines.

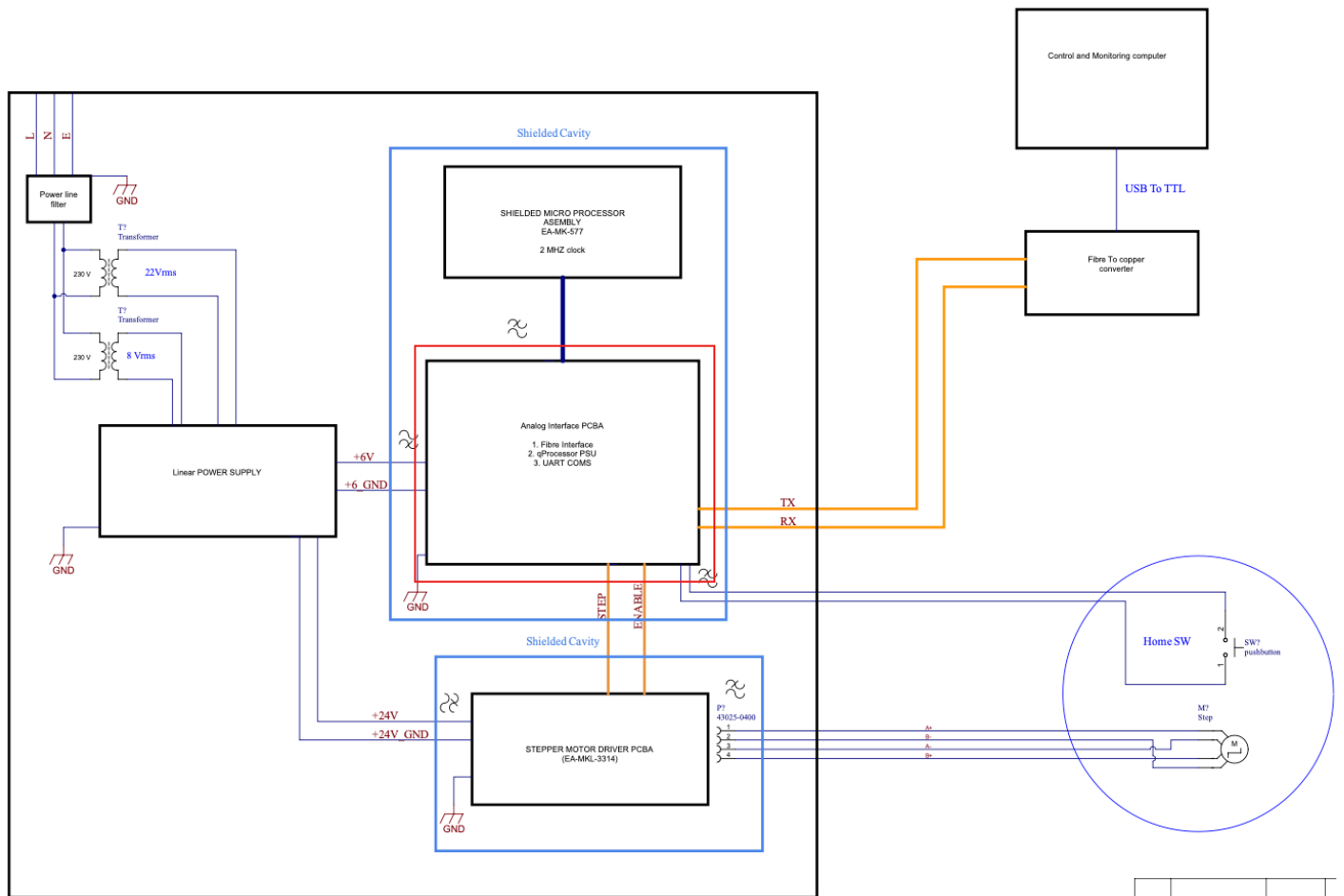


Figure 4.24: System diagram with AI shown.

The AI PCBA forms the central link between the microcontroller module, stepper motor driver, position sensors, and fibre-optic communication interfaces. Its primary functions are summarised as follows:

- 5V regulator circuit providing isolated power to the fibre-optic interfaces and microcontroller , the PSU utilises and.
- Microcontroller interface via a 25-pin D-sub connector for command and feedback signal exchange(see Figure 4.25).

- Position sensor interface with provisions for up to four independent sensors, enabling precise angular position monitoring of the turntable (see Figure 4.25).
- Stepper motor direction line.
- UART-to-fibre interface for noise-immune serial communication with external control equipment.
- Stepper motor control fibre interface, allowing electrically isolated transmission of step and enable signals.

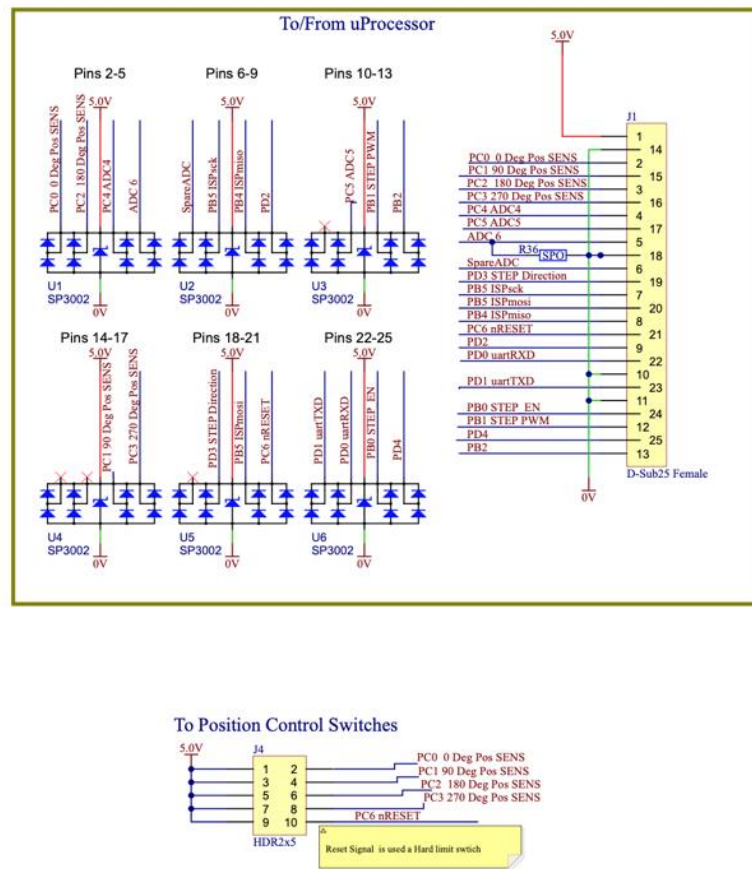


Figure 4.25: Microcontroller and position sensor interface.

The 5 V regulator circuit on the AI PCBA (shown in Figure 4.26) is implemented using the LT1965EQ low-dropout linear regulator. This device was selected for its ability to provide clean, stable, and low-noise output, which is critical for sensitive microcontroller and fibre-optic circuits. The LT1965EQ features excellent load and line regulation, a high power supply rejection ratio (PSRR), and low output noise (typically 40 μ V RMS), ensuring that fluctuations or ripple from upstream power sources do not propagate into the analogue or digital subsystems.

Additionally, the LT1965EQ's low-dropout characteristic allows it to maintain regulated 5 V output even when input voltage levels are close to the desired output. By supplying isolated and filtered power to the microcontroller and fibre-optic interface, this regulator contributes directly to the system's low-EMI design.

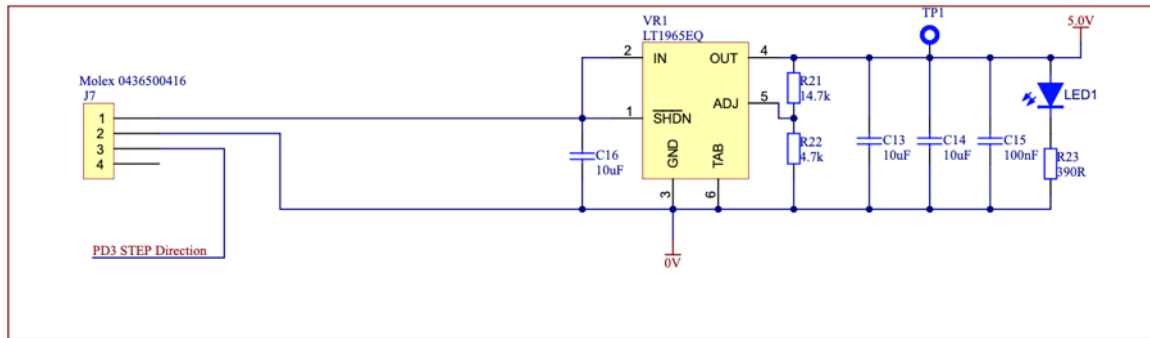


Figure 4.26: AI 5V PSU.

4.3.4.1 UART FIBRE OPTIC COMMUNICATION AND STEPPER MOTOR CONTROL

The HFBR-x4ExZ series fibre optic transmitters and receivers from Avago Technologies with SC connectors are used. On the PCB, the fibre receivers are Avago HFBR-24E2Z and the fibre transmitters are Avago HFBR-14E4Z. The transmitter uses an 820 nm wavelength light source. This will allow for UART serial communication between a PC terminal and the microcontroller to allow for precision control of the stepper motor position.

The microcontroller to stepper motor controller electronics link uses 1 mm plastic optical fibre (POF). The HFBR-0500Z Versatile Link series from Avago Technologies provides a complete low cost solution for the POF. Transmitters and receivers are packaged separately, but can be interlocked to form a duplex unit. The transmitters incorporate a 660 nm red LED and supports a signal rate of 1 MBd over a distance of 10 m. The schematic is shown in Figure 4.27.

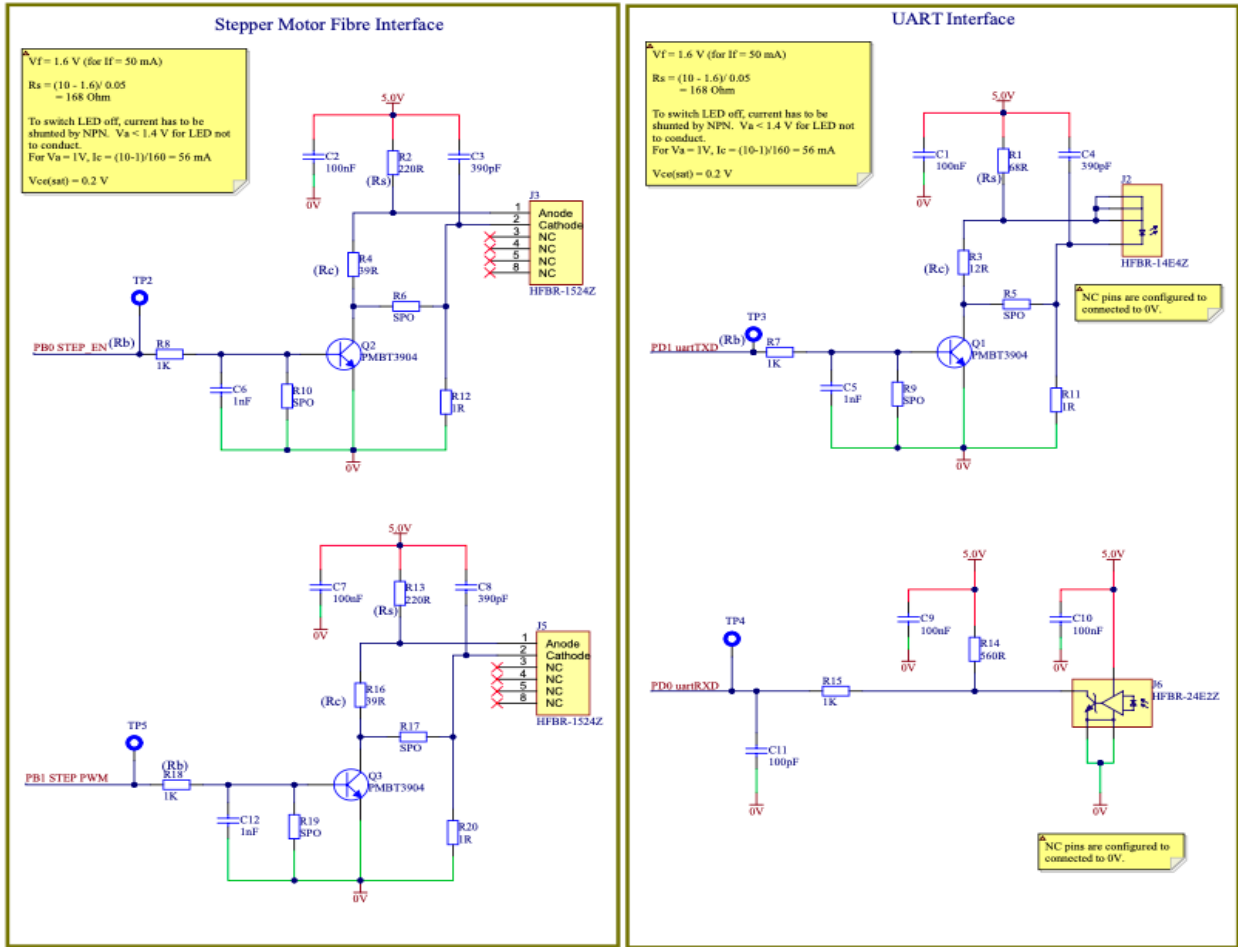


Figure 4.27: UART fibre Optic communication and stepper motor control.

4.3.5 CALIBRATION SWITCH

A basic limit switch was implemented as the zero-position reference indicator. Since the switch is mounted externally to the shielded enclosure, it introduces a potential EMI risk when triggered during normal operation and creates an unintended coupling path. To mitigate this, the switch lines are filtered both at the main enclosure output and at the analogue interface input.

4.3.6 GROUNDING ARCHITECTURE

When designing a grounding architecture for a sensitive mixed-signal system, it is important to ensure that there is not a possibility of noisy return currents sharing a common return path with sensitive analogue signals. To this end, the only enclosure-grounded circuit that the controller interfaces with is the analogue interface circuit. All other circuits that connect to the controller.

4.4 FIRMWARE DEVELOPMENT

4.4.1 SYSTEM OVERVIEW

The firmware was developed for the ATmega328P microcontroller operating at 2 MHz (discussed in 4.3.1). It implements precision rotation control for the stepper motor selected in 4.2.3. The firmware has the following core capabilities:

- PWM-based motor speed regulation
- Direction control (clockwise / anticlockwise)
- Incremental rotation to a specified angle
- Homing and calibration using a limit switch
- EEPROM-based non-volatile storage of motion parameters
- Serial command interface for runtime configuration and control

4.4.2 PIN DEFINITIONS

Pin assignments were selected based on ATmega328P hardware resources to ensure compatibility with Timer1 (used for PWM) and GPIO-driven direction and enable signals.

Table 4.6: Pin definitions.

Description	Pin	Function
PWM Output (<code>pwmPin</code>)	9	Generates PWM signal for motor speed control using Timer1
Direction Output (<code>directionPin</code>)	3	Sets rotation direction (CW / ACW)
Motor Enable (<code>enablePin</code>)	8	Enables or disables motor driver output
Home Switch (<code>homeSwitchPin</code>)	4	Detects mechanical home position (limit switch input with pull-up)

4.4.3 MOTION AND TIMING PARAMETERS

Motion control timing is characterized through the `timePerDegree` variable, which defines the duration (in ms) required for the output shaft to rotate 1°. This parameter effectively links motor mechanical speed to time-domain control and can be adjusted or calibrated at runtime.

```
float timePerDegree = 166.7; // milliseconds per degree
float currentPosition = 0.0; // tracks shaft position in degrees
```

Values for current position, PWM frequency, and timing constant are stored persistently in EEPROM, ensuring that operational parameters remain intact between power cycles.

4.4.4 EEPROM PARAMETER MANAGEMENT

During startup, the firmware retrieves essential parameters from EEPROM memory. Validation checks ensure data integrity; any erroneous values are replaced with default constants.

Table 4.7 EEPROM memory.

Parameter	EEPROM Address	Default Value	Description
currentPosition	0	0.0°	Last known angular position
pwmFrequency	sizeof(currentPosition)	746 Hz	PWM frequency used for motor drive
timePerDegree	sizeof(currentPosition)+sizeof(pwmFrequency)	166.7 ms/°	Motor time constant

EEPROM data is updated after each step or when parameters are modified through serial commands, ensuring consistent behaviour across restarts.

4.4.5 PWM CONFIGURATION AND TIMER1 OPERATION

Motor speed control is achieved via hardware PWM generated by Timer1, which is set to Phase and Frequency Correct mode (Mode 14). This setup produces symmetrical waveforms and allows accurate frequency management, making it suitable for controlling H-bridge or transistor-based motor interfaces.

The PWM period is determined by the Input Capture Register (ICR1) using the formula:

$$f_{PWM} = \frac{F_{CPU}}{2 \cdot N \cdot ICR1} \quad (4.3)$$

Where:

- F_{CPU} = 2 MHz is the system clock
- N = 1 (no prescaler)
- $ICR1$ defines the counter top value

Rearranging for ICR1:

$$ICR1 = \frac{F_{CPU}}{2 \cdot f_{PWM}} - 1$$

In code:

```
int icrValue = (F_CPU / (2 * frequency)) - 1;
ICR1 = icrValue;
OCR1A = icrValue / 2; // 50% duty cycle
```

This generates a stable PWM waveform at 746 Hz as the default setting, with a tunable frequency range from 100 Hz to 5 kHz to accommodate various motor speeds.

4.4.6 COMMAND PROCESSING LOGIC

The firmware constantly checks the serial interface for incoming ASCII commands, which are parsed in real time to manage the motor system.

Supported commands are:

Table 4.8: Serial commands.

Command	Function
CW	Continuous clockwise rotation
ACW	Continuous anticlockwise rotation
STOP	Immediately stops motor motion
CW STEP <deg>	Rotates by specified degrees CW
ACW STEP <deg>	Rotates by specified degrees ACW
FREQ <Hz>	Sets new PWM frequency (100–5000 Hz)
TIME <ms>	Updates time per degree constant
CALIBRATE	Performs homing using limit switch

Command handling example:

```
if (Serial.available() > 0) {  
    String command = Serial.readStringUntil('\n');  
    processCommand(command);  
}
```

This flexible command structure allows on-the-fly reconfiguration of speed, direction, and motion limits without recompilation.

4.4.7 ROTATION AND STEP LOGIC

Incremental rotation is controlled via time-based regulation, based on the `timePerDegree` parameter. When a step command is received, the firmware determines the necessary duration proportionally to the desired angle.

$$T_{rotation} = (\text{degrees}) \times \text{timePerDegree} \quad (4.4)$$

For instance, a 90° rotation with `timePerDegree` set to 166.7 ms will operate as follows:

$$T_{rotation} = 90 \times 166.7 = 15,003 \text{ ms}$$

During this period, the motor enable signal stays active. Once the time expires, PWM output is turned off, and the `currentPosition` variable updates to reflect the new position.

Position is constrained within a 0–360° range to prevent overflow:

```
if (currentPosition > 360) currentPosition = 360;  
if (currentPosition < 0) currentPosition = 0;
```

4.4.8 HOMING AND CALIBRATION LOGIC

The calibration routine aligns the

motor position to a known mechanical zero reference using a limit switch connected to `homeSwitchPin`. During calibration, the motor rotates counterclockwise until the switch is triggered (LOW state). When the motor stops, `currentPosition` is reset to 0° , which is then stored in EEPROM.

4.4.9 MOTOR ENABLE AND STOP CONTROL

Digital and timer-based synchronization is used to enable and disable the motor.

Enable logic:

```
digitalWrite(enablePin, HIGH);
TCCR1A |= (1 << COM1A1);
```

Disable logic:

```
digitalWrite(enablePin, LOW);
TCCR1A &= ~(1 << COM1A1);
```

The `enablePin` serves as an hardware lock ensuring the PWM output only drives the motor when explicitly enabled.

4.4.10 MATHEMATICAL MODEL

The firmware models angular motion in the time domain using a simplified approach, assuming constant motor speed and ideal driving conditions.

This model allows position estimation without encoder feedback.

Table 4.9: Firmware mathematical model.

Variable	Equation	Units
Time per degree	t_{deg} (user-defined)	ms/ $^\circ$
Rotation duration	$T_{rot} = \text{degrees} \times t_{deg}$	ms
PWM top value	$ICR1 = \frac{F_{CPU}}{2 \cdot f_{PWM}} - 1$	counts
Angular position	$\theta_{current} = \text{clamp}(\theta_{prev} \pm \text{degrees}, 0.360)$	degrees

Model Assumptions

Motor speed remains constant, with acceleration effects ignored. The link between time and angular displacement is linear. The limit switch offers a dependable zero reference point. PWM duty cycle is fixed at 50%, so motor speed is governed solely by frequency. EEPROM read/write delays and drift are insignificant. No feedback sensors, such as encoders, are used; instead, position is estimated through time integration. This model delivers deterministic and repeatable control, ideal for laboratory experiments or low-speed actuation where open-loop accuracy is sufficient.

In summary the firmware offers a compact, modular, and non-blocking implementation of motor control using the ATmega328P microcontroller. Source code of the firmware can be found in Appendix B.

4.5 CONTROL SOFTWARE DESIGN

A custom graphical user interface (GUI) shown in Figure 4.28 was created in Python with *Tkinter library* (Grayson, J., 2000) to facilitate intuitive and efficient interaction with the motor control system. This GUI is the platform for setting up serial communication, sending control commands, and viewing real- time feedback from the controller. This can also be achieved by using a terminal software (such as *tera term*) and typing commands, however the GUI makes it more user friendly and allows users to easily modify control parameters and observe system behaviour. The program is built as a single class, *MotorControlGUI*, incorporating all GUI components, communication routines, and control logic. Serial communication with the microcontroller- based motor driver uses the *PySerial library*, with available ports automatically detected via *serial.tools.list_ports* and shown in a drop-down menu. Connection management is handled through dedicated buttons, and error checks ensure invalid configurations are caught. Once connected, a background thread continuously monitors incoming serial data without disrupting the GUI.

Motor commands are sent as ASCII strings, including predefined commands listed in Table 4.8. Users can also enter parameters like rotation angle, PWM frequency, or timing via entry fields and buttons.

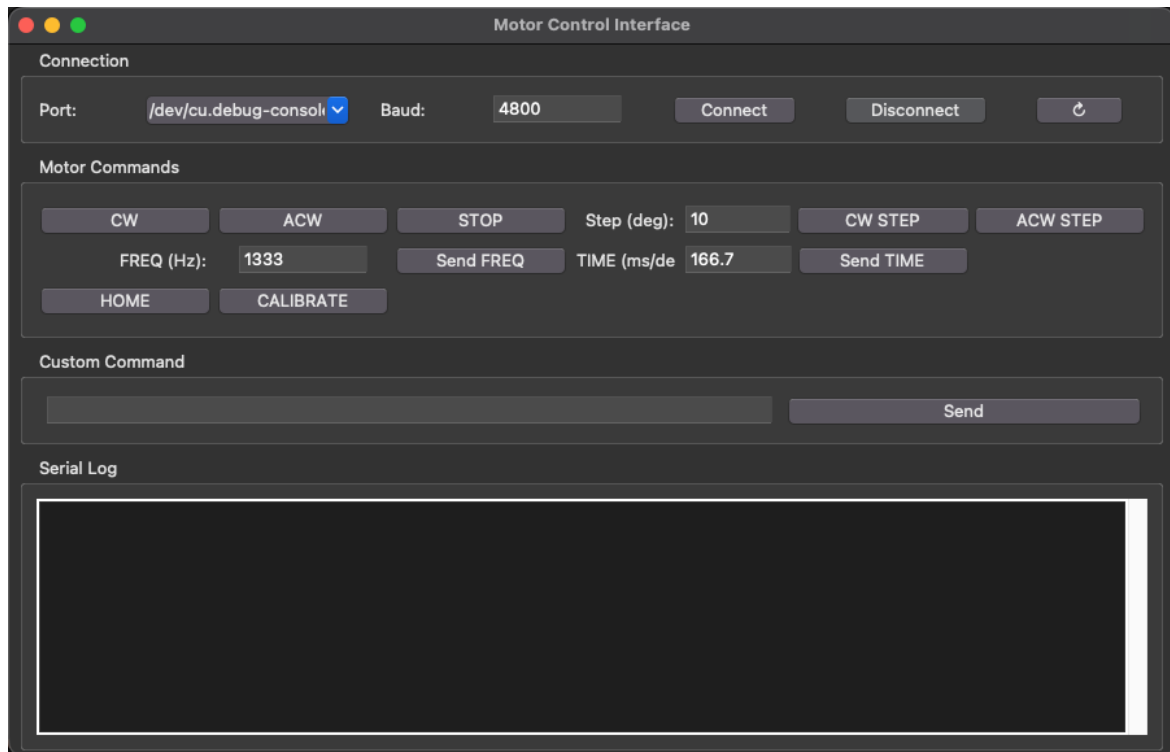


Figure 4.28: Motor control python GUI.

Responses such as acknowledgments or position updates appear in a scrollable log window, recording all communication for debugging. To maintain responsiveness, serial communication operates in a background thread, while GUI updates are managed with Tkinter's `after()` method to ensure thread safety. This setup prevents the interface from freezing during continuous data exchange or long motor operations. Error handling enhances safety by rejecting invalid inputs, issuing warnings for incorrect settings, and providing an immediate stop command.

Thus the GUI offers a dependable, user- friendly interface between the operator and the motor control firmware. Its structured command execution and user input support both experimental testing and routine control. This GUI can be easily adapted and improved at no cost, making it ideal for research institutions. Source code of the control software can be found in Appendix C.

CHAPTER 5 INTEGRATION, TESTING AND VERIFICATION

This chapter outlines the processes used to integrate the design and test the basic performance of the ATT subsystems. After completing the design and prototyping phases, the next step was to verify that each subsystem namely, mechanical, electrical, and control operated correctly independently and as part of the integrated system. The verification efforts were based on the design requirements from Chapter 3 and aimed to confirm that the system complied with all derived subsystem functional requirements.

5.1 INTEGRATION AND SUB SYSTEM VERIFICATION

5.1.1 POWER SUPPLY UNIT (PSU)

The PSU system supplies DC voltages to both the control and motor drive subsystems. It consists of three primary components:

- **An IEC-filtered input power connector.**
- **A custom-wound toroidal transformer**
- **A linear regulator-based PSU PCBA, +24 VDC for the stepper motor driver, and +6 VDC for the analogue interface PCBA and microcontroller assembly.**

During testing, verification of the PSU outputs was done with an calibrated multi meter. showed The outputs measured 24.02 V and 6.08 V, confirming voltage regulation within tolerances. Thermal testing showed that the +6 V regulator went into thermal shutdown due to poor heat dissipation. An auxiliary heatsink was added to the TO-220 package, stabilising the temperature at about 35°C during continuous operation, confirmed by a contact thermocouple.

5.1.2 STEPPER MOTOR AND DRIVER

To test the compatibility between the selected stepper motor and the DRV8818-based driver, initial lab tests were conducted. For these test the motor driver PCBA was setup in standalone mode, with the onboard 555 timer oscillator generating step pulses as described by (Liebenberg and van Staden, 2018). The motor was set to rotate at 60 rpm, and rotation was confirmed visually. To evaluate mechanical performance under load, torque was measured with a handheld torque driver, starting at 1.2 Nm and increasing to 1.8 Nm to simulate the expected torque range of the ATT. These findings verified the mechanical and electrical compatibility of the motor-driver system and confirmed that the torque output was adequate for the system.

5.1.3 ANALOGUE INTERFACE AND MICROCONTROLLER

To support the initial firmware development and validation, the Arduino platform with and Atmega328p was used. This allowed for easier prototyping and debugging before full system

integration. The Arduino was connected directly to the Analogue Interface PCBA via jumper wires, the DRV8818 stepper motor driver, and the power supply was connected with its dedicated harness assemblies. Firmware was developed in a modular way, enabling isolated testing of each subsystem prior to full integration. The initial focus was on validating serial communication, particularly UART initialisation, transmission, and reception. A baud rate of 4800 bps was selected which is lower than the usual 9600 bps, this was to enhance communication reliability given the microcontroller's reduced 2 MHz clock. Signal quality was verified by measuring the UART Tx signal (shown in Figure 5.1) at both the sender (PC) and the receiver (microcontroller) pin.

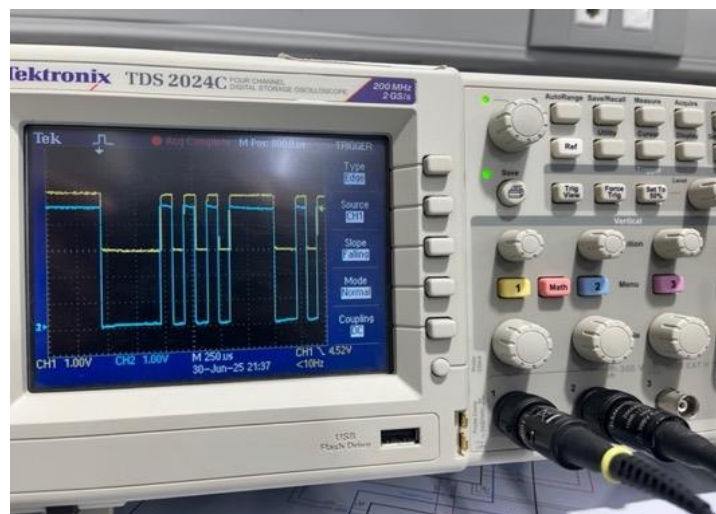


Figure 5.1: UART fibre link confirmation *signal integrity verified at both transmit and receive ends using fibre-optic interface.*

The firmware incorporated the following features :

- Position readback for angular tracking.
- Homing routines using limit switches.
- PWM generation for motor speed control.
- Enable/direction logic for motion control.
- Error handling and feedback routines for robust operation under varying command sequences.

The motor PWM signal operation was verified through oscilloscope measurements, confirming duty cycle and frequency accuracy .

Table 5.1: Sub system verification summary.

Component	Test	Measurement / Result	Notes / Conclusion
PSU +6 V	Output Voltage	6.08 V	Within specification
PSU +6 V	Thermal Characterisation	28° C with heatsink	Safe operating temperature after heatsink installation
Stepper Motor	Rotation Speed	60 rpm	Confirmed via observation and timing
Stepper Motor	PWM Accuracy	Verified via oscilloscope	Duty cycle and frequency correct for operation
Stepper Motor	Enable and direction	Confirmed via observation	Confirmed via observation(signals changes logic level when commands are issued via serial communication.
Stepper Motor	Torque	1.2–1.8 Nm	Adequate for load requirements
Firmware	Serial Communication	4800 bps stable	Baud rate reduced for reliability
Firmware	Position / Homing	Verified	Correct operation and error handling confirmed

This subsystem validation phase confirmed that all subsystems functioned according to design specifications as summarised in Table 5.1, These tests established a basis for system integration.

5.1.4 SUBSYSTEM INTEGRATION AND ASSEMBLY

After verifying individual subsystems, the next step was integration and assembly. Enclosures were carefully machined with precision hand tools to fit connectors, cable feed-throughs, and mounting features. All components were installed and the firmware was deployed.

5.1.4.1 FIRMWARE DEPLOYMENT

The final firmware was compiled in the Arduino IDE into a .hex file and uploaded (using Atmel studio) onto the standalone ATmega328P microcontroller (EA-MK-577) via the Atmel AVR Dragon programmer in ISP mode The microcontroller was set up to run without a bootloader, allowing the application firmware to start immediately after reset. Fuse bits were adjusted for use with the 2 MHz external crystal oscillator.

The applied fuse values were:

- Low Fuse (0xFF): External full-swing crystal oscillator (CKSEL = 1111), maximum startup time (SUT = 11), clock divide by 8 disabled (CKDIV8 = 1).

- High Fuse (0xDE): SPI programming enabled (SPIEN = 0), boot section size 2048 words (BOOTSZ = 00), no bootloader, EEPROM preserved during chip erase (EESAVE = 1).
- Extended Fuse (0xFD): Brown-out detection enabled at 2.7 V (BODLEVEL = 101).

5.1.4.2 ELECTRONIC ASSEMBLIES

The Analogue Interface PCBA, microcontroller, stepper motor driver, and PSU were mounted in RFI-shielded enclosures for electromagnetic and mechanical stability. Electrical and mechanical interfaces were aligned. Grounding used a single-point strategy to prevent ground loops and reduce currents. Interfaces were routed to minimise electromagnetic coupling, stress, and vibration. Before power-up, continuity and isolation checks were done, confirming correct connections, no shorts, and proper grounding.

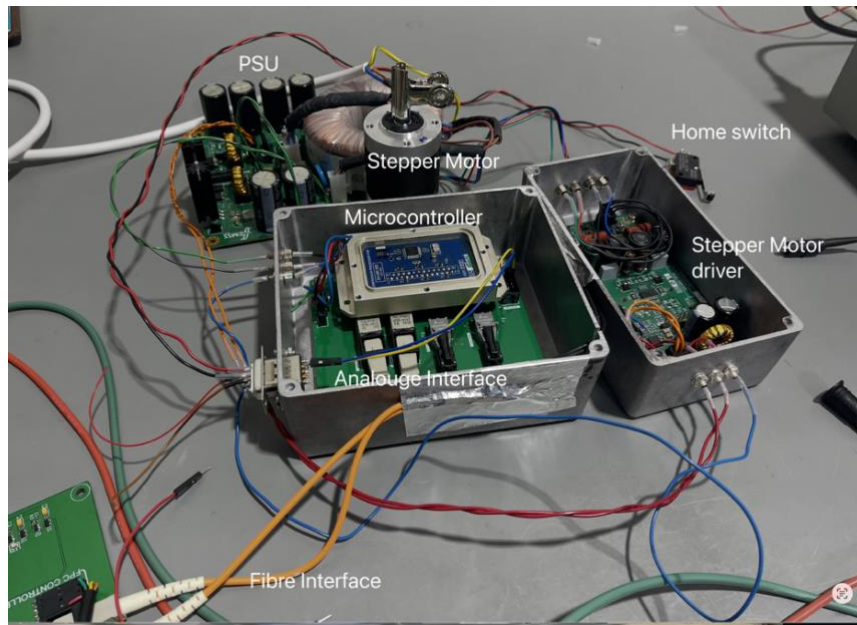


Figure 5.2: Electronic sub-assembly verification in progress.

5.1.5 FINAL SYSTEM INTEGRATION AND ASSEMBLY

After verifying subsystem compatibility and firmware deployment, the final integration of the ATT involved mechanical modifications and precise fitting of subsystems into the main shielded enclosure, designed for EMC. Machining with a drill press, cordless drill, and metal file prepared the enclosure for installing filtered connectors, fibre-optic feedthroughs, and interface panels without compromising shielding. The sequence started with assembling the power and fibre-optic interface panel, including a Schurter IEC filtered inlet and ODC-4 fibre connectors (Amphenol, 2025), mounted on removable panel for easy maintenance.

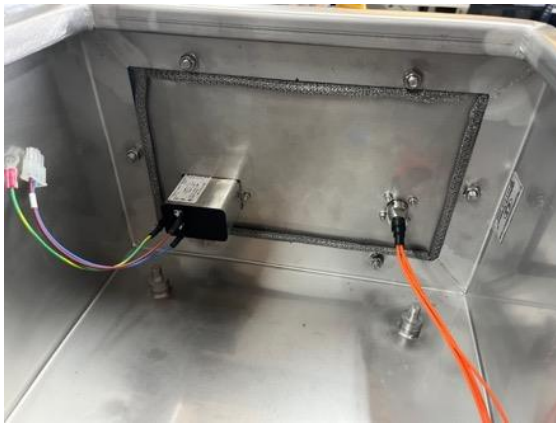


Figure 5.3: Installation of fibre and power entry.

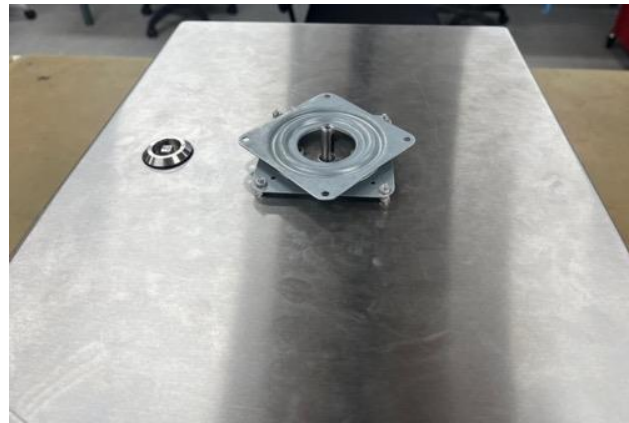


Figure 5.4: Installation of motor and tabletop bearing.

The motor and turntable bearing assembly was then installed into the enclosure lid as shown in Figure 5.3. The Lazy Susan bearing was coupled the NEMA 17 stepper motor (Stepper Online, 2025) shown in Figure 5.4. Using a custom 3D printed interface. Subsystems including the microcontroller (EA-MK-577), analogue interface PCBA, and DRV8818-based stepper motor driver were mounted onto the enclosure interface plate (shown in Figure 5.5) before installation within the enclosure. Each module was housed in a dedicated RFI-shielded cavity, with interconnections routed through filtered D-sub connectors and feedthrough filters.



Figure 5.5: Mounting of subsystems to mounting plate.

The final assembly shown in Figure 5.6 & Figure 5.7 involved securing subsystems, verifying alignment, and confirming electrical continuity after making soldered connections. This modular setup reduced manufacturing complexity and ensured serviceability, electromagnetic containment, and robustness of the ATT system.



Figure 5.6: Final assembly internals (no lids vs lids).



Figure 5.7: Final assembly.

5.2 COST OF SYSTEM COMPONENTS

Commercial EMC-compliant antenna test turntables (such as those covered in Section 2.7) cost around USD 9 000 ($\approx$ 170 000 ZAR). The proposed shielded ATT was developed for about 30 000 ZAR ($\approx$ \$1 615), saving nearly 82% compared to commercial systems. Table 5.2. Shows a breakdown of the material costs.

Table 5.2: Cost breakdown of Antenna test turntable.

Description	ZAR	USD
Shielded microcontroller assembly	R 4000	$\approx$ \$220
Stepper motor driver PCBA	R 5000	$\approx$ \$280
Power supply PCBA	R 3500	$\approx$ \$195
Analogue interface PCBA	R 2800	$\approx$ \$155
Transformer assembly	R 1800	$\approx$ \$100
Input power line filter	R 600	$\approx$ \$35
Inline filters and filtered connectors	R 4000	$\approx$ \$220
Enclosures	R 6000	$\approx$ \$335
Fibre optic interfaces	R 600	$\approx$ \$35
Consumables	R 500	$\approx$ \$28
Total	R 29800	$\approx$ \$1 615

Due to the affordability of the ATT, it makes it ideal for use in academic and research environments.

CHAPTER 6 TESTING AND RESULTS VERIFICATION

This chapter provides an overview of the test procedures followed to validate the Antenna Test Turntable (ATT) design and presents and discusses the results obtained.

6.1 FUNCTIONAL TESTING

Following the integration of the ATT system, a series of functional tests were performed to verify the functional performance requirements. The tests involved verifying serial communication via fibre-optic UART, confirming that the stepper motor rotated in both directions, testing the homing mechanism, assessing angular accuracy, repeatability and confirming rotation under maximum load. Functional tests were performed before conducting EMC tests.

6.1.1 TEST SETUP

This section shows the test setup required to perform functional testing.

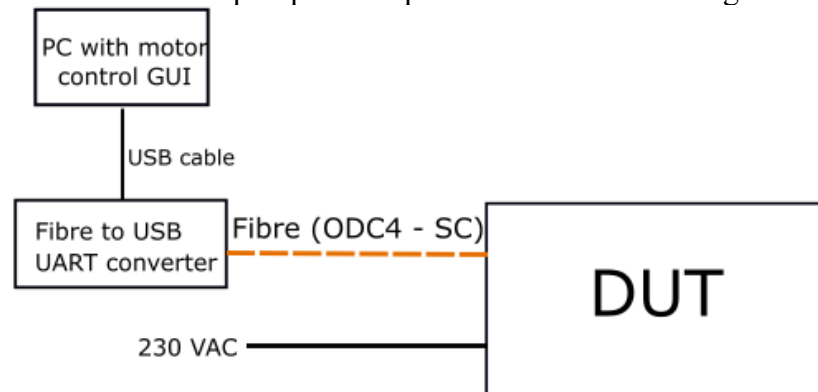


Figure 6.1:Functional test setup.

6.1.2 REQUIRED TEST EQUIPMENT

The following equipment was required to perform functional testing:

- Antenna test turntable
- PC with python
- Motor control python software
- ODC 4-SC fibre cable
- IEC power cable
- Fibre to USB UART converter
- Protractor
- 25 kg dummy weight

6.1.3 TEST PROCEDURE

The following steps were followed for functional testing:

- Connect the fibre-optic cable and AC power supply to the ATT as per section 6.1.1.
- Open the motor control GUI and select the appropriate serial port.
- Power on the ATT

- d) Confirm serial communication by observing responses in the GUI terminal window.
- e) Start the motor rotating clockwise (CW) using the GUI and check that it turns continuously. Then, send a stop command and verify that it stops moving.
- f) Repeat step (e) for anticlockwise (ACW) rotation and verify correct directional change.
- g) Run the calibration process by pressing the “Calibrate” button. Ensure that the turntable spins until the homing switch activates at the 0° reference point.
- h) Using a calibrated protractor, incrementally rotate the turntable in 1° CW steps from 0° to 20°, verifying positional accuracy at each step
- i) Continue rotation in 10° increments from 20° to 180°, confirming angular displacement after each step using the protractor.
- j) Rotate the turntable ACW from 180° back to 0° and confirm that it stops precisely at the home position.
- k) Rotate the turntable in 90° CW increments and verify angular accuracy at each step.
- l) Load the turntable with 25 kg of weight and rotate the table 360 degrees and confirm the table rotates accurately with no slippage.

6.1.4 OBSERVATIONS AND RESULTS

The functional test procedure effectively verified all key operational features of the ATT. Serial communication was established between the PC and the microcontroller successfully via the fibre-optic UART interface, bidirectional data transfer confirmed through the GUI terminal. Figure 6.2 illustrates the test setup used for functional testing.

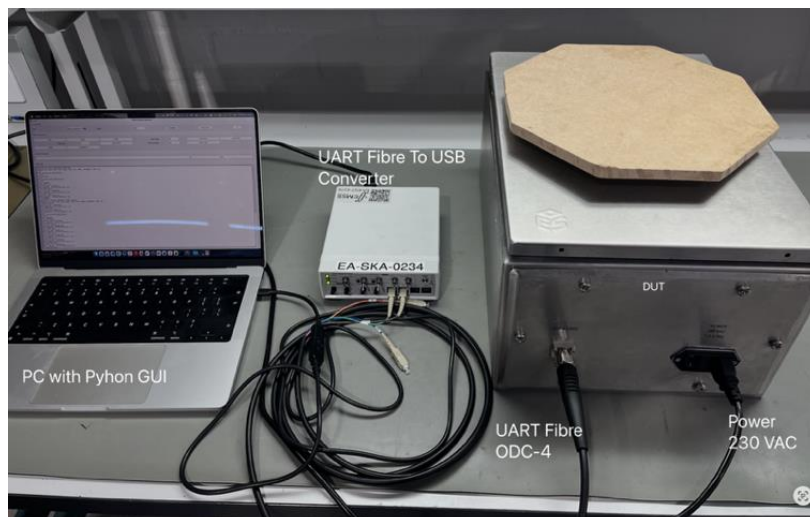


Figure 6.2: Practical evaluation test setup confirmation.

The stepper motor responded to control commands, rotating continuously in both clockwise and anticlockwise directions, and stopped immediately when the stop command was issued. Figure 6.3 shows the GUI terminal after executing the commands and the terminal response.

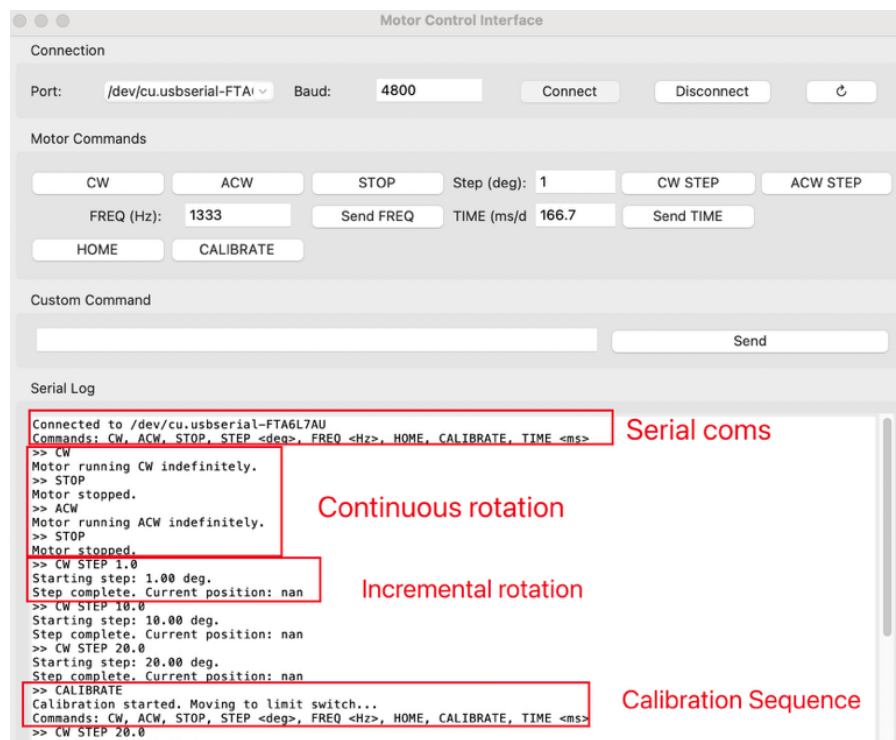


Figure 6.3: GUI terminal response.

The calibration routine worked as intended, rotating the platform until the homing switch was activated, setting the 0° reference position shown in Figure 6.4. Incremental rotation tests with a calibrated protractor verified that the angular accuracy is within 1° resolution.



Figure 6.4: Angular accuracy measurements and loaded test in progress.

Also shown in Figure 6.4 is the loaded ATT test setup, the ATT was loaded with 25 kg and a rotation sequence was performed. No motor slippage was observed. Rotational accuracy was maintained throughout the test. Refer to Table 6.1 for a summary of the completed functional tests.

Table 6.1: Functional test summary.

Test Description	Result
Serial communication via fibre-optic UART interface established	Pass
Bidirectional data exchange confirmed via Python GUI terminal	Pass
Stepper motor continuous clockwise (CW) rotation	Pass
Stepper motor continuous anticlockwise (ACW) rotation	Pass
Immediate stop on command	Pass
Calibration routine triggered homing switch at 0° reference	Pass
Incremental rotation (1° steps from 0° to 20°) verified with protractor	Pass
Incremental rotation (10° steps from 20° to 180°) verified with protractor	Pass
Reverse rotation from 180° to 0° returned to home position	Pass
90° step increments verified for repeatability and precision	Pass
25 kg loaded rotation test	Pass

These results confirm that the ATT meets its functional design specifications for accurate rotation, position feedback, load-bearing rotation, and communication.

6.2 EMC TEST: NEAR FIELD PROBING

Near-field probing was conducted on the ATT with and without shielding lids to evaluate the effectiveness of the implemented shielding and filtering strategies. These tests were guided by the methodology outlined in Section 2.5.1.1 The results demonstrated a significant reduction in emissions when shielding was applied, confirming the effectiveness of the EMI containment measures.

6.2.1 REQUIRED TEST EQUIPMENT

The following equipment was required to perform near field probing measurements.

- a) Antenna test turntable
- b) PC with python
- c) Motor control python software
- d) ODC 4-SC fibre cable
- e) IEC power cable
- f) Fibre to USB UART converter
- g) Spectrum analyser Rohde & Schwarz FSV-4
- h) N-type to SMA coaxial cable
- i) Custom H-near field probe

6.2.2 TEST SETUP

This section shows the test setup required to perform near field probing measurements.

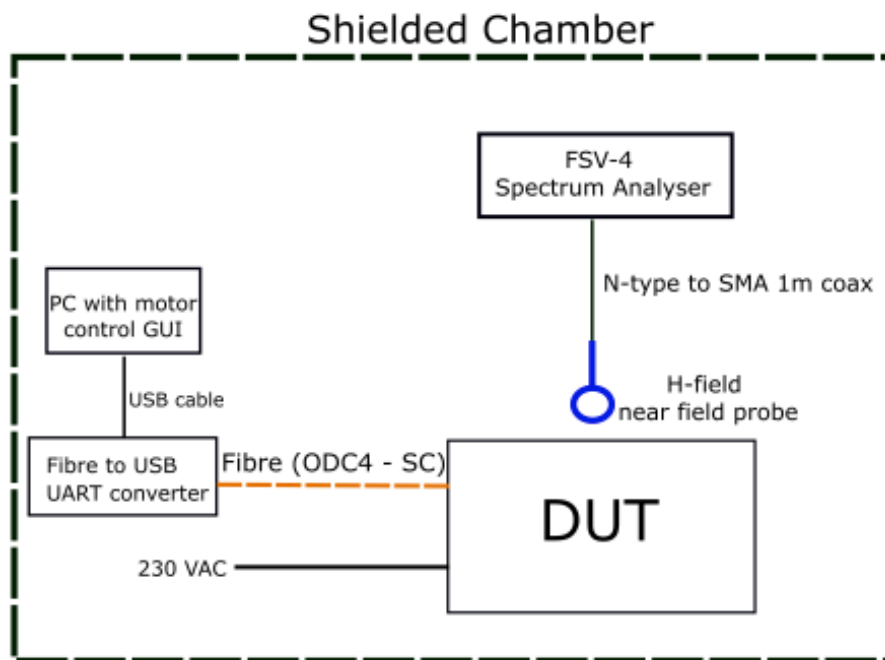


Figure 6.5: Near field probing test setup.

6.2.3 TEST PROCEDURE

The test setup was connected as shown in Figure 6.5 and near field tests completed in configurations shown in Table 6.2. The spectrum analyser setup is shown in Table 6.3.

Table 6.2: Near field tests.

Test	Description / Configuration
a)	Microcontroller without Lid vs Lid
b)	Stepper Motor Driver Lid Off vs Lid On, Idle vs Running
c)	Automated Antenna Turntable (Idle vs Running)

Table 6.3: Near field tests spectrum analyser setup.

Parameter			
Units	dBm		
Ref Level	-50 dBm		
Trace Mode	Max Hold		
Trace Detector	Max Peak		
Sweet time	0.01 s		
Sweep type	Single		
Preamplifier	On		
RF Attenuation	0 dB		
Resolution Bandwidth	100 kHz		
Frequency Range	1-10 MHz	1-100 MHz	1-1000 MHz

6.2.4 OBSERVATIONS AND RESULTS

Figure 6.6 Shows the near field test setup. The test setup was done inside of a shielded chamber to reduce the effect of external factors interfering with the measurements.

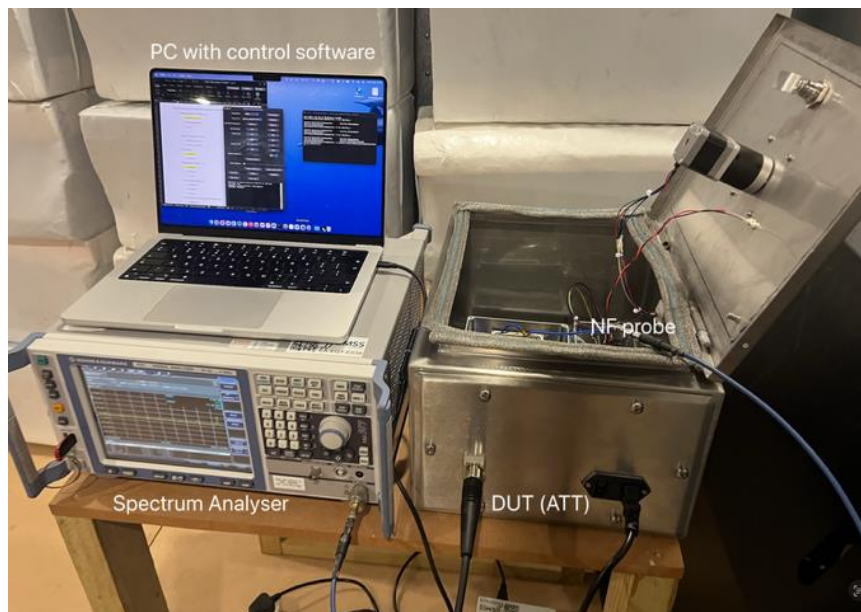


Figure 6.6: Near field probe test setup confirmation.

a) Microcontroller

As shown in Figure 6.7 shows NF results for between 0 and 10 MHz, the 2 MHz crystal oscillator signal and its associated harmonics are clearly visible when the microcontroller is measured without its shielding lid (orange trace). The harmonics appear at higher amplitudes due to the characteristics of the near-field (NF) probe. It's not that the circuit radiates harmonics more strongly than the fundamental frequency; rather, the probe's transfer function Favors higher frequencies. This is due to its smaller loop area and increased sensitivity at higher frequencies, which causes the spectrum analyser to display harmonics with artificially elevated amplitudes compared to the true fundamental. The probe was intentionally selected to enhance coupling at the harmonic frequencies of interest.

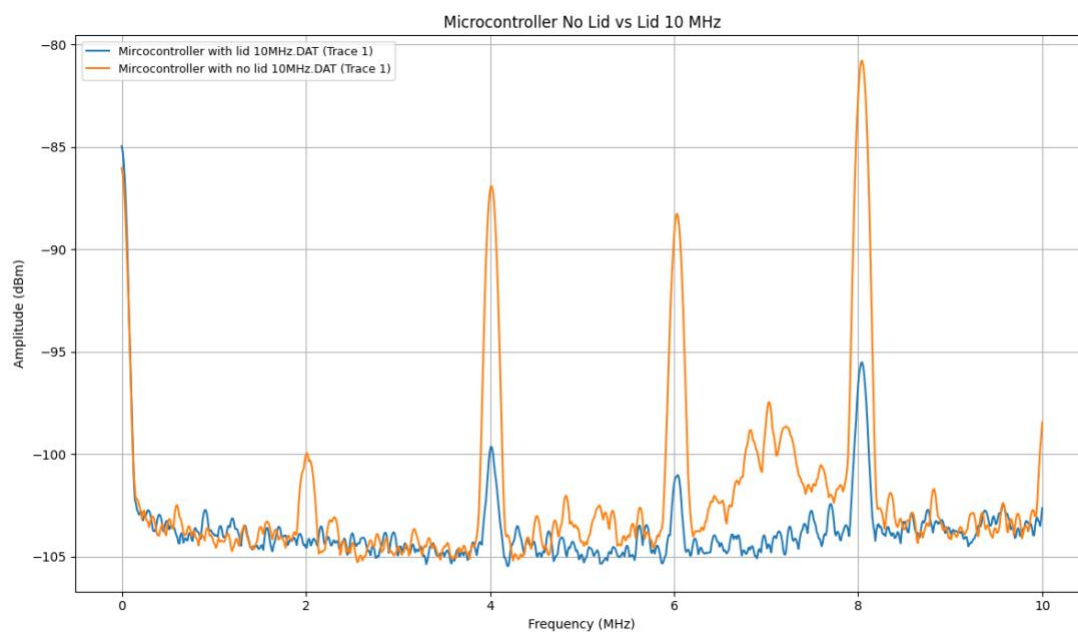


Figure 6.7: Microcontroller NF (10 MHz).

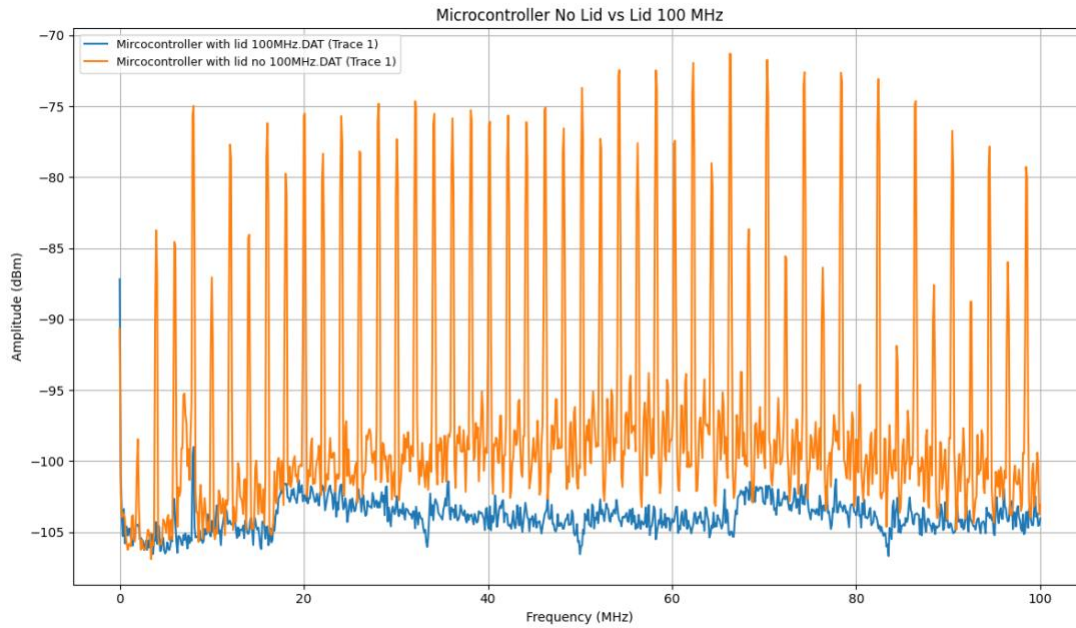


Figure 6.8: Microcontroller NF (100 MHz).

Figure 6.8 illustrates the harmonic components of the 2 MHz crystal oscillator across the frequency range of 2 MHz to 100 MHz. The orange trace represents measurements taken without the shielding lid, while the blue trace shows results after the lid was applied, with the lid applied all measured signals fall below the 100 dB level, indicating that the shielding and filtering applied to the microcontroller are effective over this frequency range.

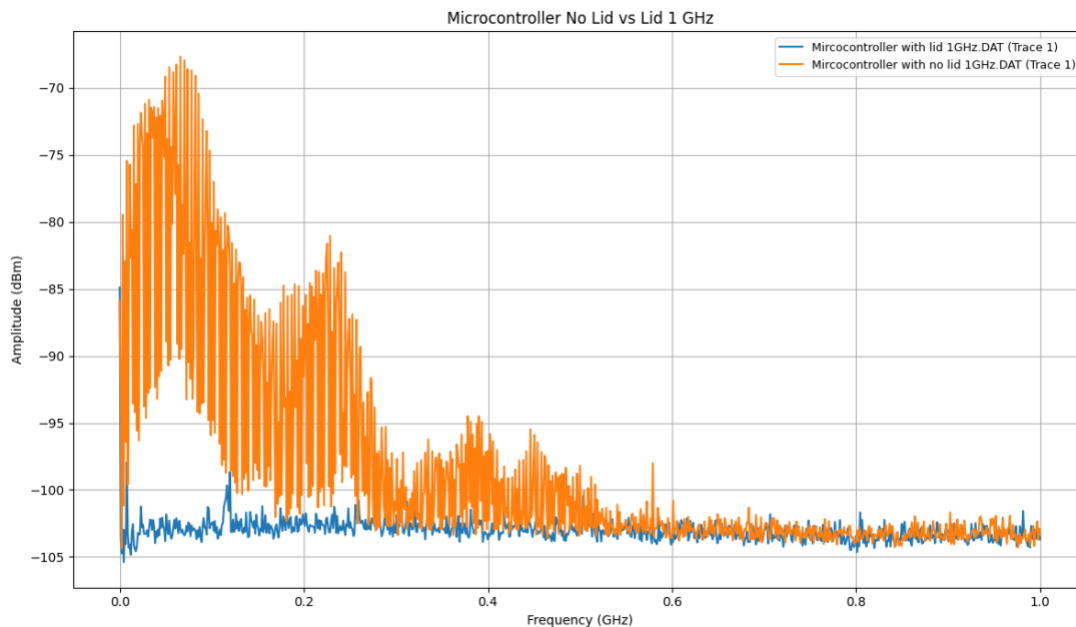


Figure 6.9: Microcontroller NF (1 GHz).

Figure 6.9 illustrate the NF results over the 1 MHz to 1 GHz range, as can be seen the unshielded measurement (orange trace) reduces as the frequency decreases, The shielding and filtering effectiveness can also be seen over this wider frequency range. Once the shielding lid

is installed, the effectiveness of the EMI containment becomes evident, with attenuation of up to 30 dB observed shown by the blue traces.

b) Stepper Motor Driver Lid Off vs Lid On, Idle vs Running

The stepper motor driver was probed with and without its shielding lid, both on the PCBA and across the input and output harnesses. As shown in Figure 6.10, the orange trace represents emissions measured without the lid, while the blue trace shows the results with the lid installed over the 1-100 MHz range. The shielding effectiveness is clearly demonstrated, with significant attenuation of high-frequency components. Additionally, the low-pass filtering is evident signals in the kilohertz range are allowed to pass, while higher-frequency emissions are effectively suppressed. This confirms that both the shielding and filtering strategies are functioning as intended.

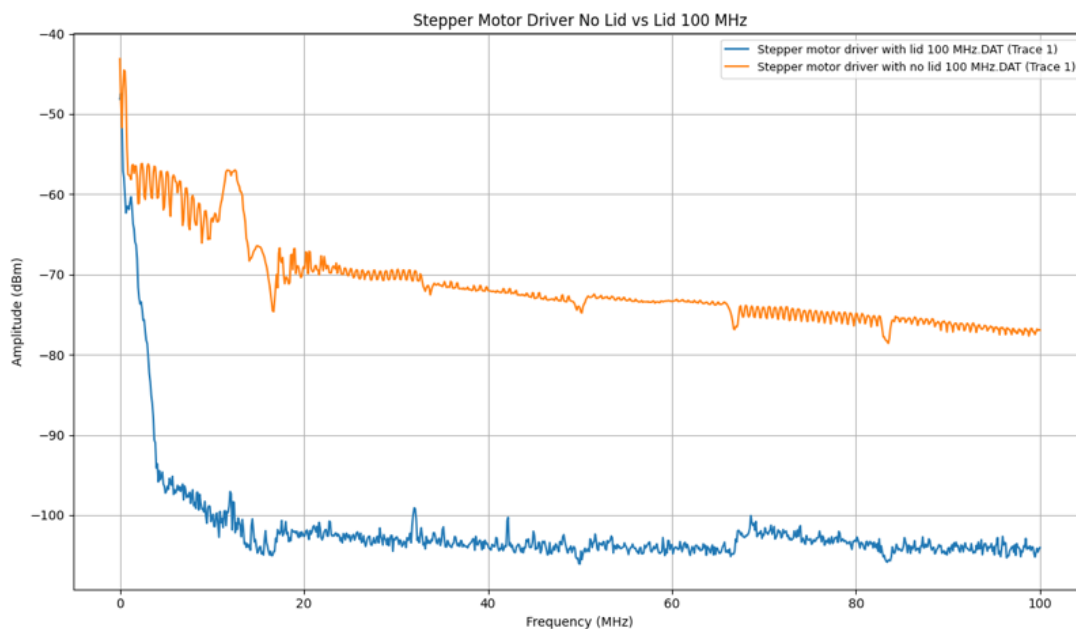


Figure 6.10: Stepper motor running with lid vs no lid (100 MHz).

Further, Figure 6.11 presents a comparison of three configurations: the motor driver running without a lid (green), running with the lid installed (orange), and idle with no lid (blue) over the 0-1 GHz frequency range. It can be seen that only low-frequency signals pass through, and there is no significant difference between the running (with a lid) and idle (without lid) states, indicating that the shielding effectively contains emissions even during active operation.

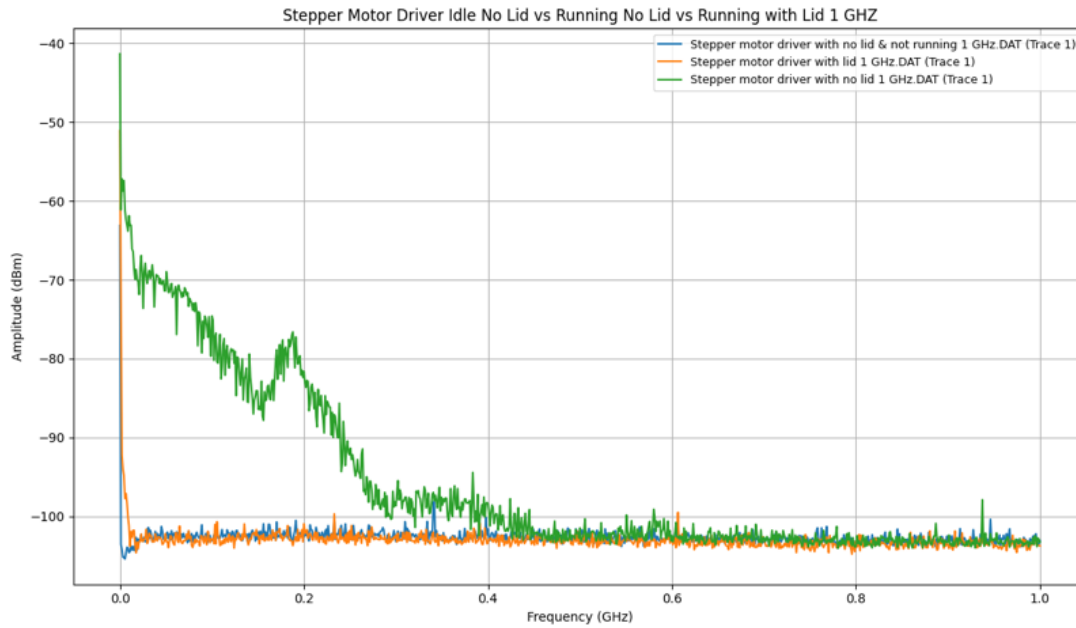


Figure 6.11: Stepper motor running with lid vs no lid vs idle (1 GHz).

c) Automated Antenna Turntable (Idle vs Running)

The final near-field test was conducted by probing all internal harnesses of the ATT during both idle (motor powered but not rotating) and active running states. Figure 6.12 shows the results of the NF tests between idle (blue) and running (orange) states over the 1-10 MHz frequency range. It can be observed that only low-frequency components were visible in the near-field measurements during running state. This is attributed to the stepper motor driver and is not of the concern due to the low frequency of the emissions.

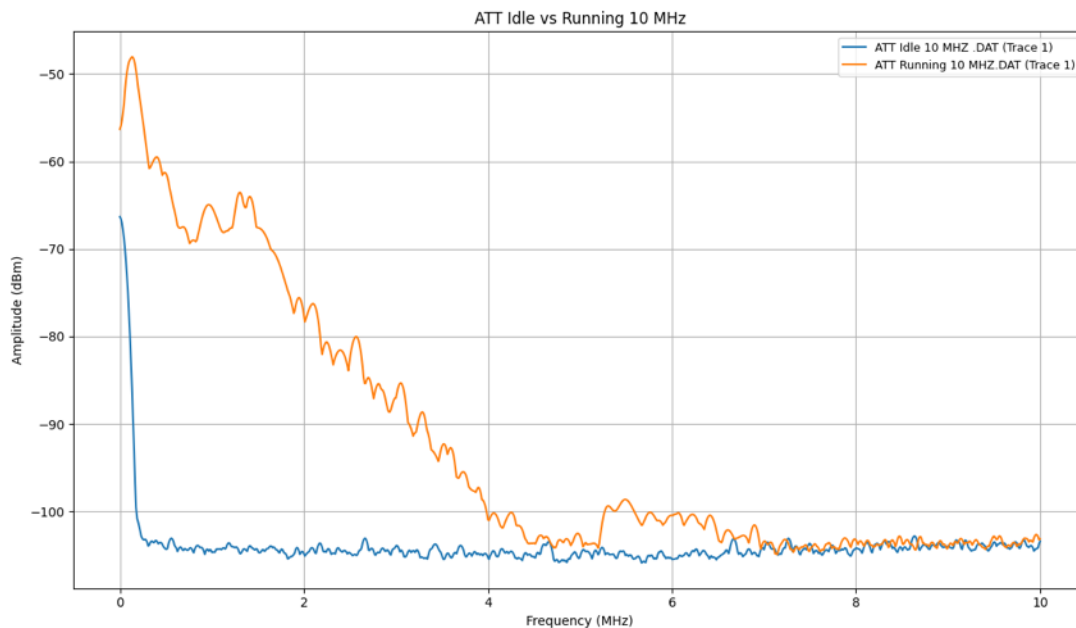


Figure 6.12: ATT running vs idle (10 MHz).

Figure 6.13 provides the NF probe results obtained over the 0-1 GHz frequency range between the idle (orange) and running (blue) states again only low frequency components below 10 MHz is visible. A small peak was observed at 220 MHz however, its origin was not investigated further as the levels were sufficiently low.

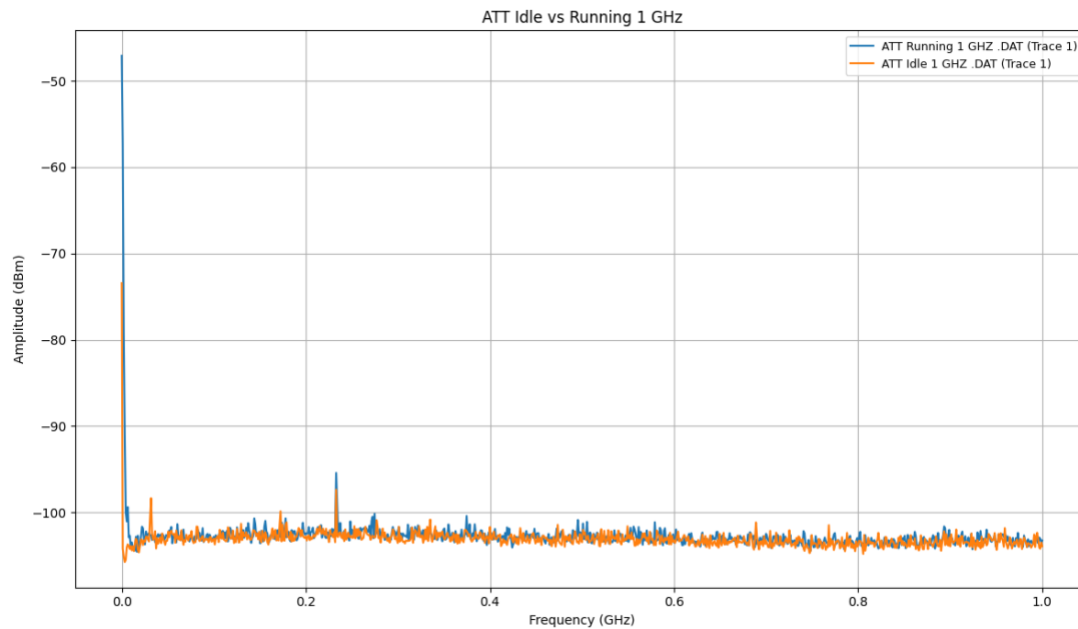


Figure 6.13: ATT running vs idle (1 GHz).

In conclusion the near-field probing tests confirmed that the implemented shielding and filtering strategies significantly attenuate emissions. Future work may further reduce the measurement noise floor by applying longer averaging periods or narrower resolution bandwidths, which were not implemented here to maintain consistency across all measurements.

6.3 EMC TEST: COMMON MODE CURRENT

Common mode current (CMC) were conducted on the ATT, guided by the methodology outlined in Section 2.5.1.1. The results demonstrated that the implemented shielding and filtering measures were effective in reducing conducted emissions, with all measured values remaining below the defined threshold.

6.3.1 REQUIRED EQUIPMENT

The following equipment was required to perform common mode current measurements.

- Antenna test turntable
- PC with python
- Motor control python software
- ODC 4-SC fibre cable
- IEC power cable
- Fibre to USB UART converter
- Spectrum analyser Rohde & Schwarz FSH8
- N-type to N-type coaxial cable
- ETS Lindgren calibrated current probe capable of operation up to at least 1 GHz.

6.3.2 TEST SETUP

This section shows the test setup required to perform common mode current measurements.

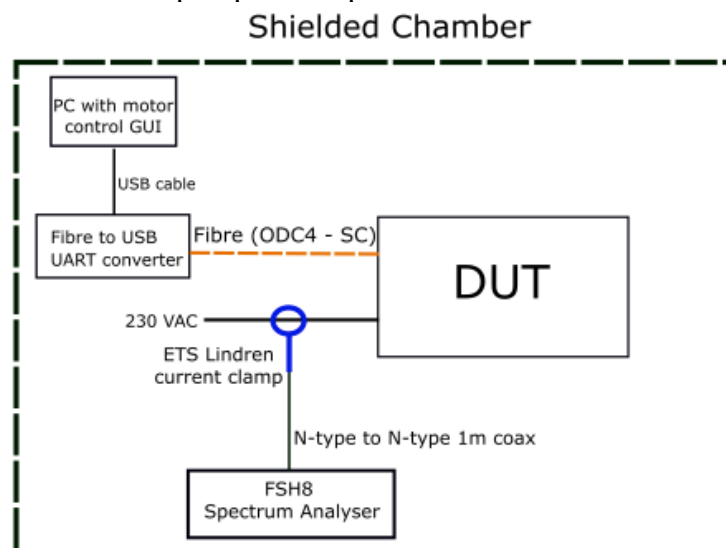


Figure 6.14: CMC Test setup.

6.3.3 TEST PROCEDURE

The test setup was connected as shown in Figure 6.14 and CMC tests completed in configurations shown in Table 6.4. The spectrum analyser setup is shown in Table 6.5. During the measurements, the cable should pass approximately through the centre of the current probe.

Table 6.4: CMC tests.

Test	Description / Configuration
a)	External power cable
b)	Internal power cable
c)	Analogue interface input
d)	Stepper motor driver input
e)	Stepper motor driver output

Table 6.5: CMC spectrum analyser setup.

Parameter			
Units	dB μ V		
Ref Level	-50 dB μ V		
Trace Mode	Max Hold		
Trace Detector	Max Peak		
Sweep time	20 s		
Sweep type	Single		
Preamplifier	On		
RF Attenuation	0 dB		
Frequency Range	1-185 MHz	185-370 MHz	370-1000 MHz
Resolution Bandwidth	300 kHz	300 kHz	1 MHz

6.3.4 OBSERVATIONS AND RESULTS

Figure 6.15 shows the CMC test setup. The test setup was done inside of a shielded chamber to reduce the effect of external factors interfering with the measurements. The measurements was converted from dB μ V to dB μ A using the calibrated transfer impedance of the current probe.



Figure 6.15: CMC setup confirmation.

CMC measurement results are presented in Figure 6.16 to Figure 6.20. No peaks exceed approximately 14 dB μ A across the measured frequency range. The 14 dB μ A specification line was selected as a conservative threshold, consistent with limits applied to cable harnesses on an MK dish installation.

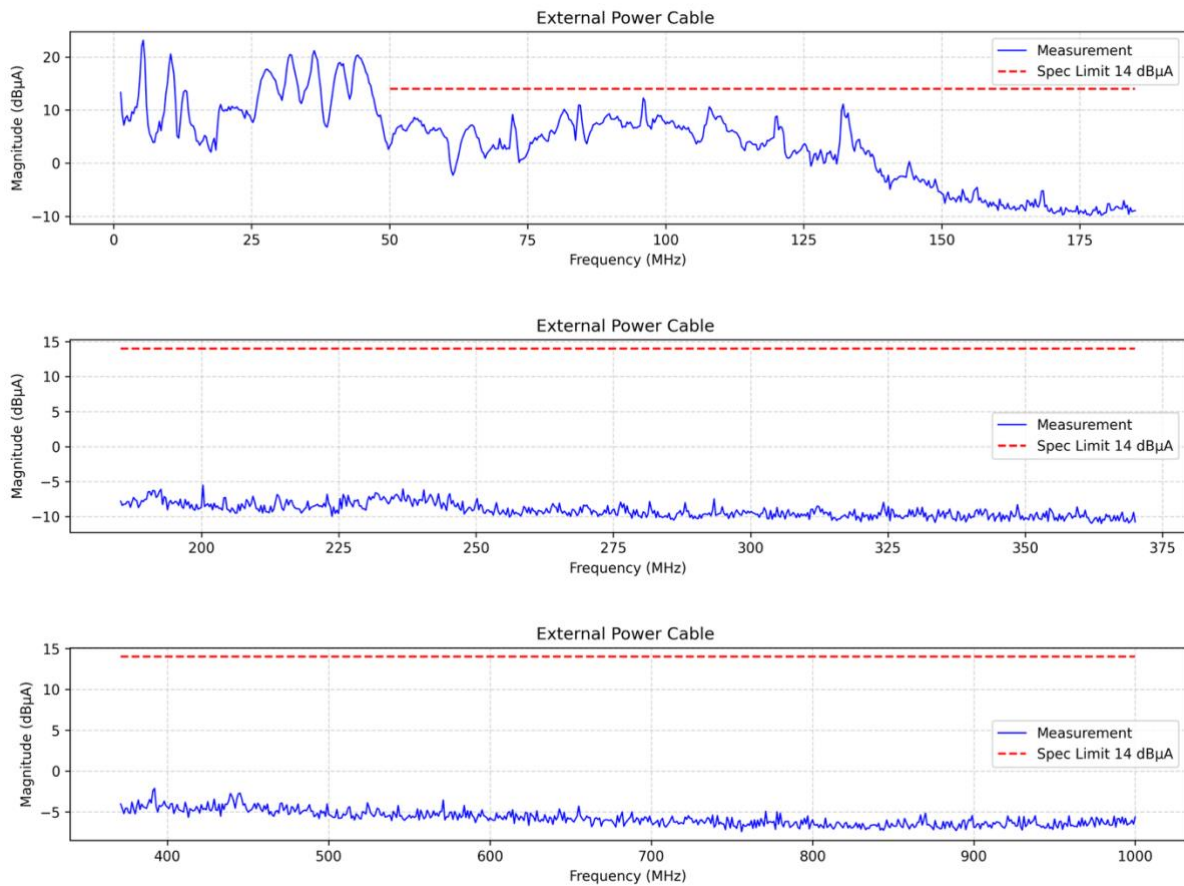


Figure 6.16: External power cable CMC results.

Figure 6.16 shows the CMC results for the power cable that supplies power to the ATT, it can be observed that some peaks are present in the lower frequency range up to 130 MHz, however these are below the conservative limit of 14 dB μ A. The performance of this cable is critical because its direct exposure to the operational environment increases the risk of electromagnetic interference, which can affect measurement accuracy.

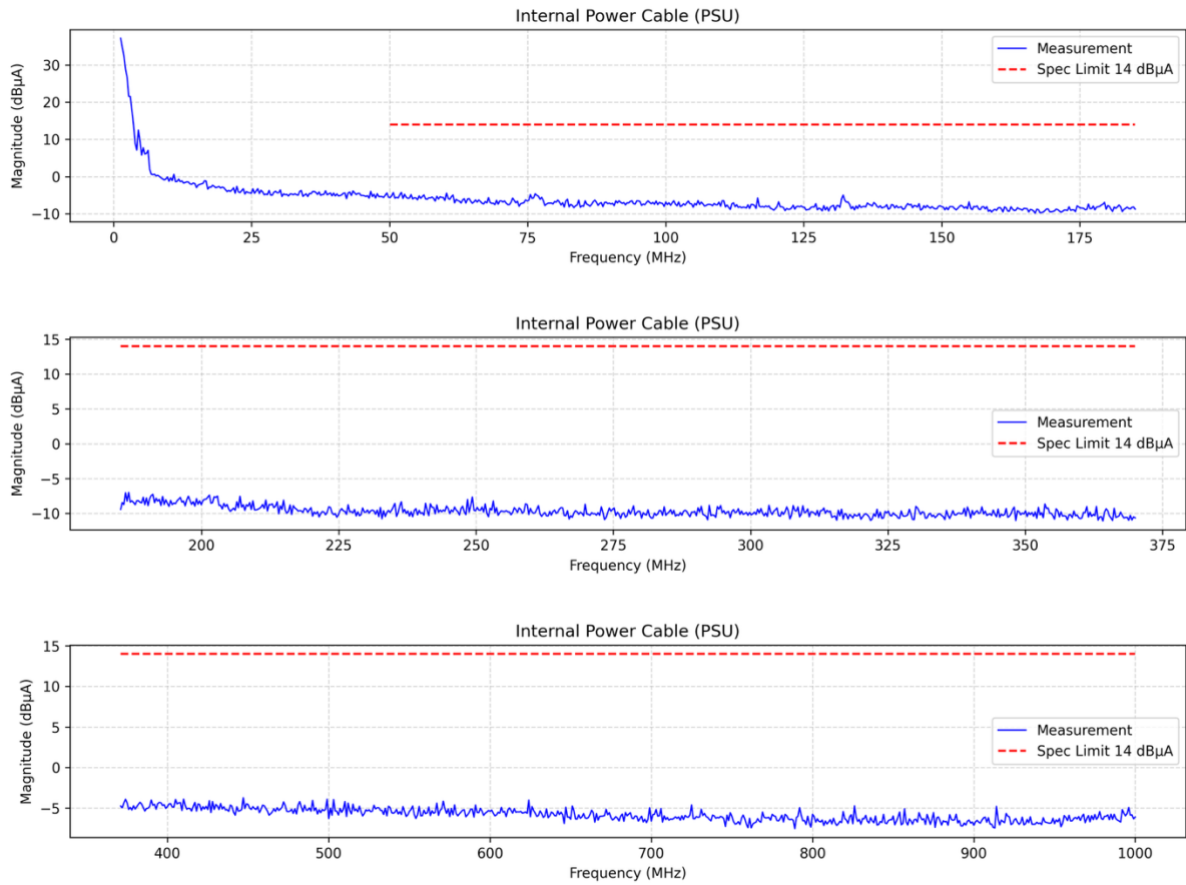


Figure 6.17: Internal power cable CMC results.

Figure 6.17 shows the results for the internal power cable, between inline power filter and the PSU PCBA, no peaks of concern was observed.

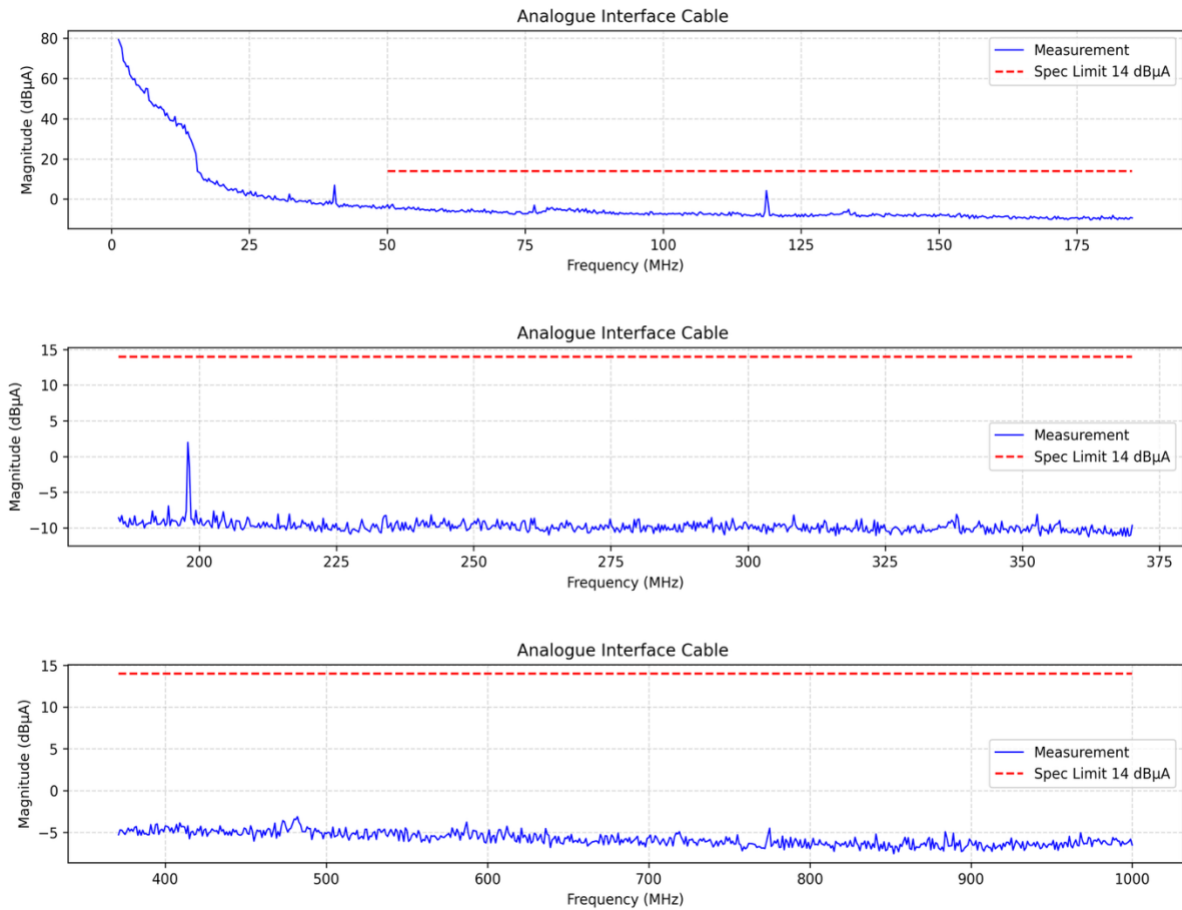


Figure 6.18: Analogue interface cable CMC results.

Figure 6.18 presents the CMC measurement data for the cables between the analogue interface assembly, PSU and stepper motor driver, a few peaks at 120 and 200 MHz can be observed, since it is well below the 14 dBμA limit, it is not of concern and thus not investigated.

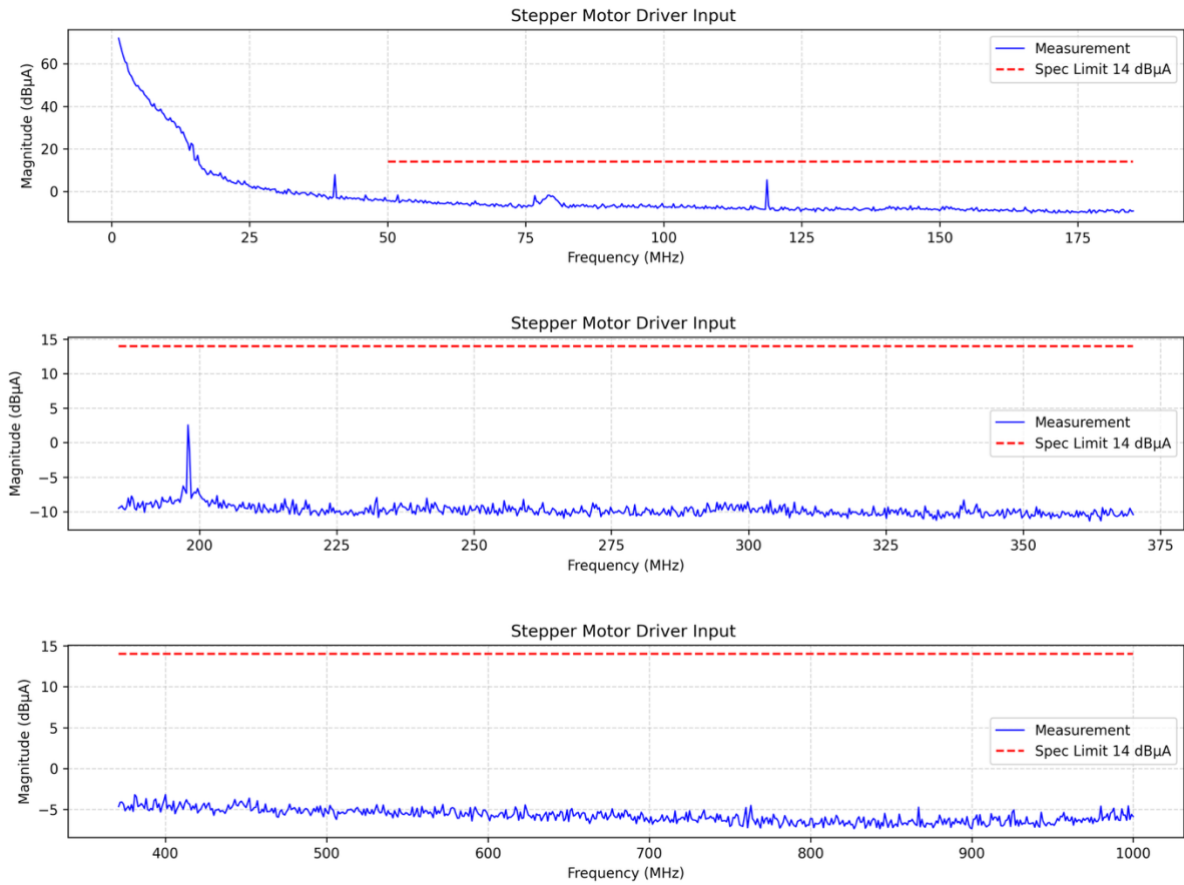


Figure 6.19: Stepper motor driver input cable CMC results.

Figure 6.19 presents the CMC result for the stepper motor input cable, (power, and direction control) a few peaks at 120 and 200 MHz can be observed, since it is well below the 14 dBμA limit, it is not of concern and thus not investigated.



Figure 6.20: Stepper motor driver output cable CMC results.

Figure 6.20 presents the CMC results for the cable between the stepper motor and motor driver, no peaks are observed in the frequency range of interest.

These results indicate good CMC performance, with all measured values remaining below the defined limit. This demonstrates effective suppression of conducted emissions and confirms the suitability of the implemented filtering and shielding measures. Notably, the only external connection to the system is the power cable, which also exhibits low CMC levels, verifying the effectiveness of the selected input power line filter. These findings indicate that common-mode emissions are unlikely to couple into adjacent subsystems or radiate through the power harness, contributing to overall compliance of the system's EMI performance.

6.4 EMC TEST: CONTINUOUS RADIATED EMISSIONS

Radiated emissions tests were conducted by the SARAO RFI team at the SARAO Cape Town reverberation chamber. All test equipment was provided by the RFI team, and post-measurement data was processed by the same team.

6.4.1 REQUIRED EQUIPMENT

The following equipment was required to perform radiated emissions tests:

- a) Antenna test turntable
- b) PC with python
- c) Motor control python software
- d) ODC 4-SC fibre cable
- e) IEC power cable
- f) Fibre to USB UART converter
- g) Tektronix RTSA RSA5115B
- h) PC for RFI analysis , chamber and RTSA control
- i) Reverberation chamber with stirrer
- j) Antenna - G-Log Periodic dipole antenna
- k) Low Noise Amplifier: Wenteq
- l) RF cables and adaptors as required

6.4.2 TEST SETUP

This section shows the test setup required to perform radiated emissions tests.

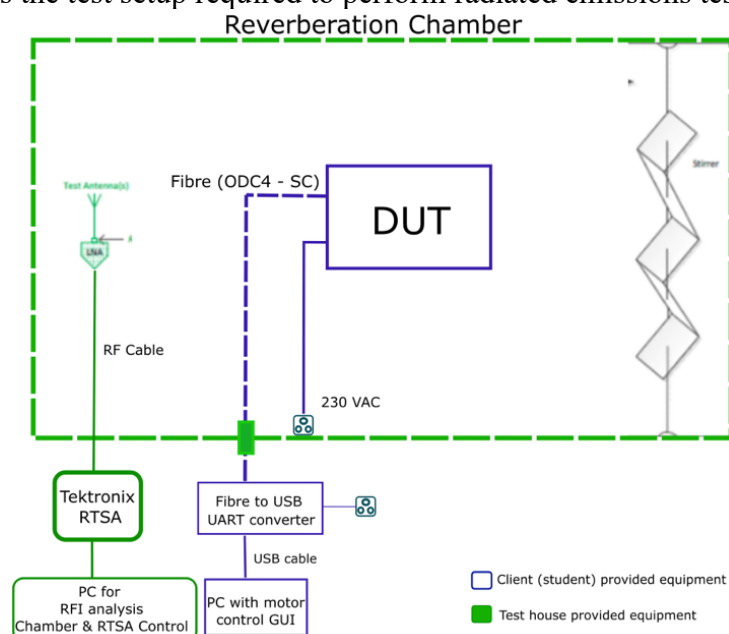


Figure 6.21: Radiated emissions test setup.

It is important to note that the reverberation chamber used for radiated emissions testing measures $2.8\text{ m} \times 5.35\text{ m} \times 2.1\text{ m}$ (W $\times$ L $\times$ H), with a theoretical lowest usable frequency (LUF) of 181 MHz and a measured LUF of 130 MHz. Although the chamber is calibrated from 50 MHz, it provides a reliable indication of compliance for pre-compliance testing purposes.

6.4.3 TEST PROCEDURE

The following steps were followed to evaluate the radiated emissions of the Antenna Test Turntable (ATT) in accordance with CISPR 32 Class B limits:

- a) Confirm the test setup
 - Ensure all equipment is correctly connected and configured.
- b) Baseline measurement (ATT powered off) no LNA.
 - Turn on the chamber stirrer.
 - Perform a baseline measurement using the following specifications:
 - Limit: CISPR 32 Class B
 - Below 1 GHz: Peak detection, RBW 120 kHz / Quasi-peak limit
 - Above 1 GHz: Peak detection, RBW 1 MHz / Peak limit
- c) Idle mode measurement (ATT powered on, motor off) no LNA.
 - Power on the ATT and configure it to idle mode.
 - Perform measurements using the same CISPR 32 Class B specifications as above.
- d) Baseline measurement (ATT powered off) with LNA
 - Power on the ATT and configure it to idle mode.
 - Turn on the chamber LNA
 - Perform measurements using the same CISPR 32 Class B specifications as above.
- e) Idle mode measurement (ATT powered on, motor off) with LNA
 - Power on the ATT and configure it to idle mode.
 - Perform measurements using the same CISPR 32 Class B specifications as above.
- f) Idle mode measurement (ATT powered on, motor off) with LNA
 - Power on the ATT and configure it to idle mode.
 - Turn on the chamber LNA
 - Perform measurements using the same CISPR 32 Class B specifications as above.
- g) Running mode measurement (motor rotating)
 - Turn off the LNA and stirrer.
 - Configure the ATT to running mode.
 - Turn on the chamber LNA

- Perform measurements using the same CISPR 32 Class B specifications.
- h) Data processing
 - Correct the raw data for:
 - LNA gain factor
 - Cable loss
 - Chamber calibration factor
 - Convert measured values (in dBm) to electric field strength (E-field) for comparison against the CISPR 32 Class B limit line.

6.4.4 OBSERVATIONS AND RESULTS

The test setup was configured as stated in Figure 6.21 and is shown in Figure 6.22.

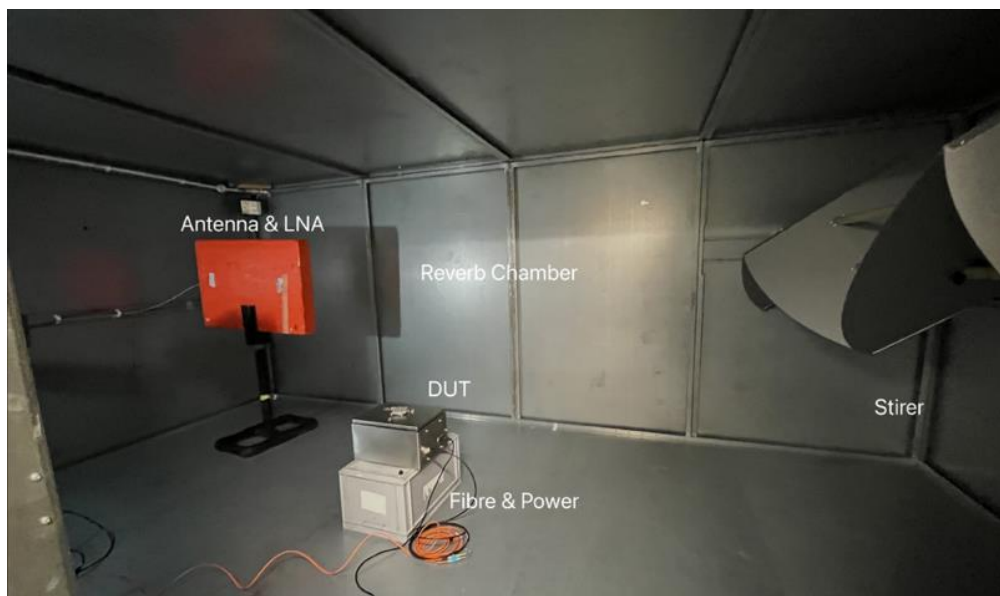


Figure 6.22: Radiated emissions test setup confirmation.

Since no significant difference was observed between measurements (b) and (c) as presented in Figure 6.23 & Figure 6.24 respectively, the LNA was installed, and the measurements were continued.

Initial tests were performed without the LNA to establish a baseline and confirm whether emissions were detectable without amplification. This precaution is critical because large emissions can damage the LNA and test equipment. The EMI was undetectable and thus required an LNA to detect emissions.

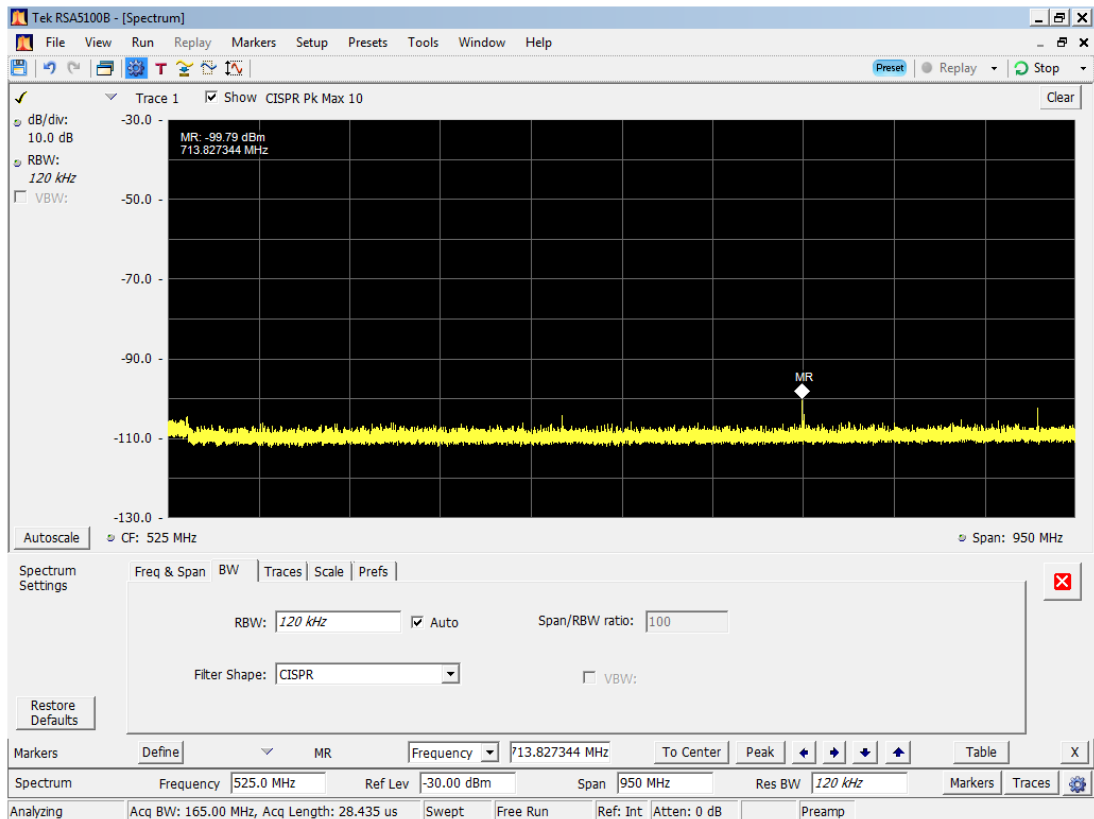


Figure 6.23: Baseline measurements (no LNA).

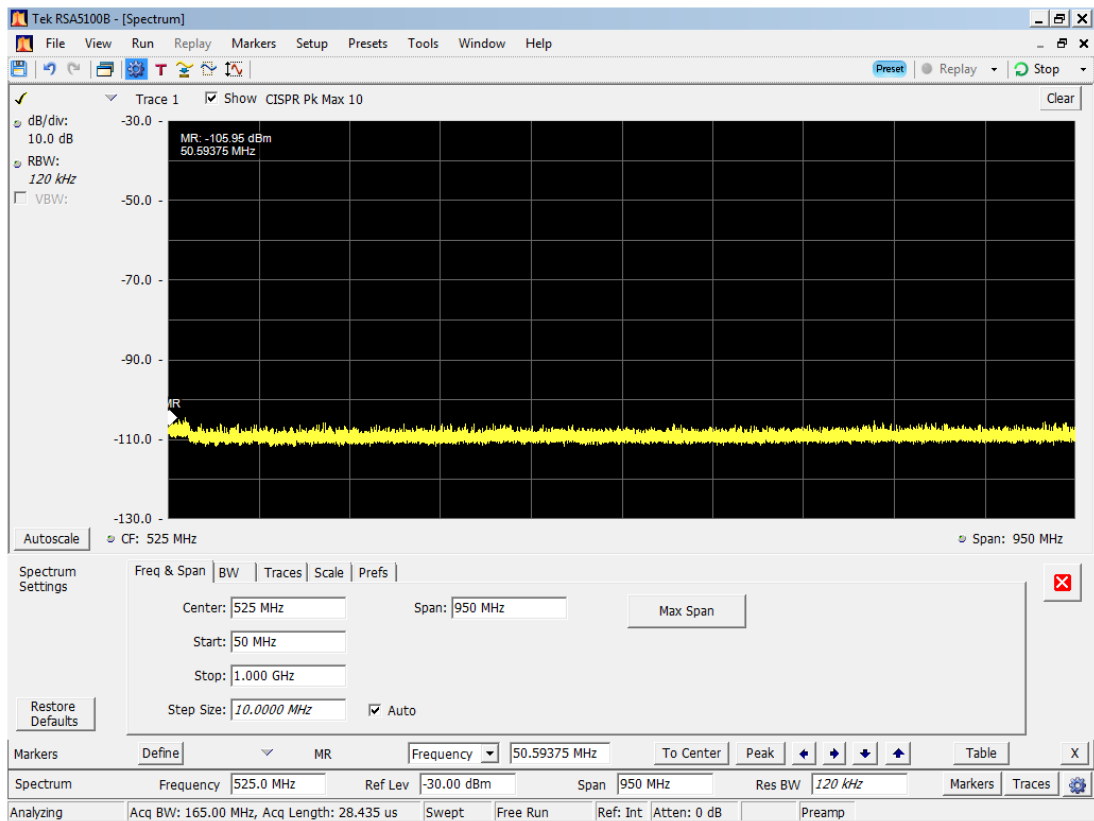


Figure 6.24: Idle mode measurements (no LNA).

Measurement data for test procedure (6.4.3) section d) & e).

Figure 6.25 presents the post-processed data compared against the CISPR 32 radiated emission limits. The plot shows the chamber background (blue trace) and the ATT emissions (black trace) across the frequency range of 50–100 MHz, with a resolution bandwidth (RBW) of 120 kHz. Although small peaks are visible slightly above the background noise level, all measured emissions remain well below the applicable CISPR 32 limit line, confirming compliance while the ATT is in idle mode.

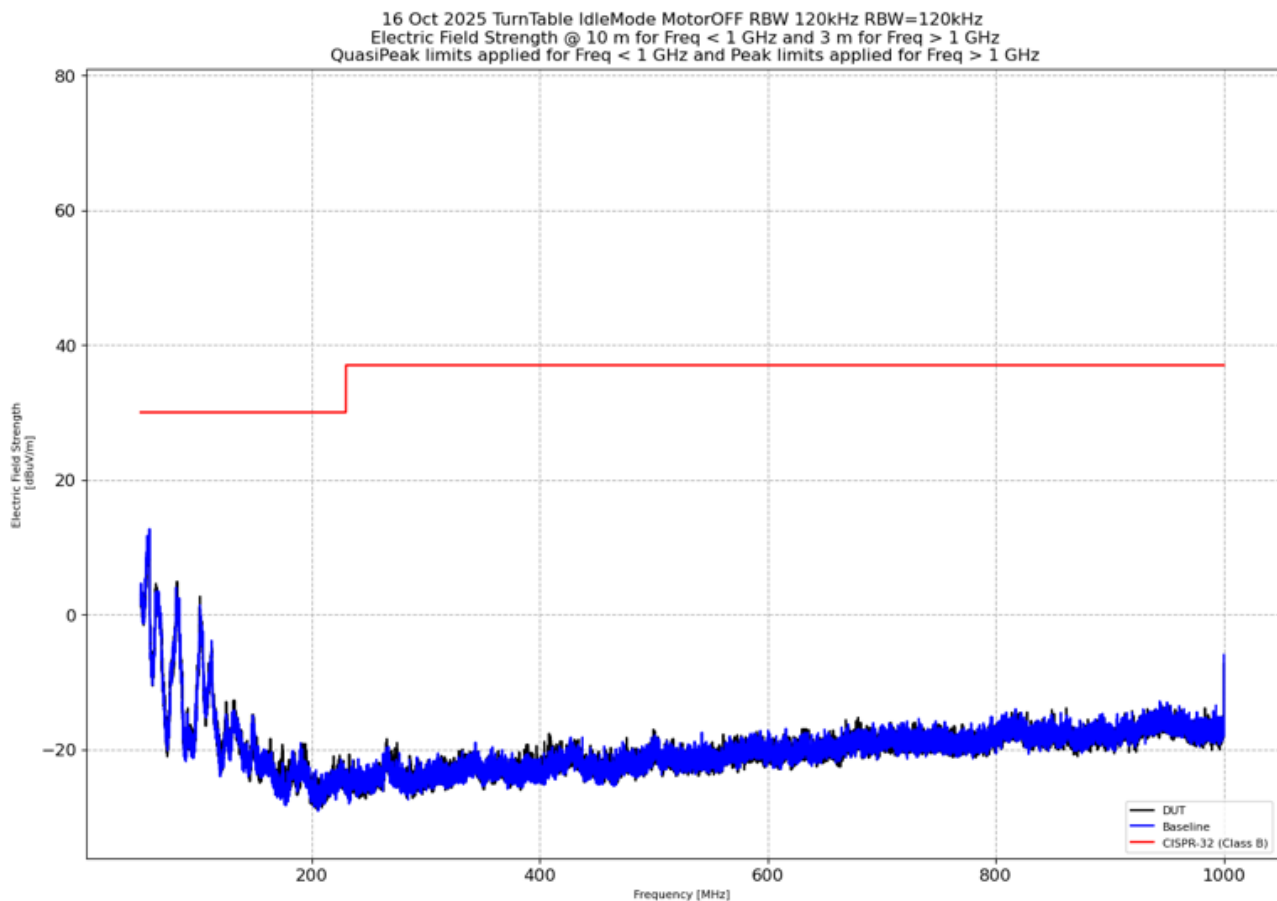


Figure 6.25: ATT idle mode emissions vs CISPR 32 limits (50 - 1000 MHz).

Additionally, radiated emissions testing was extended up to 6 GHz, which is the upper frequency limit of the SARAO reverberation chamber and well above the design requirements of the ATT. As shown in Figure 103, no distinguishable differences between the chamber background and the emissions from the device under test can be observed.

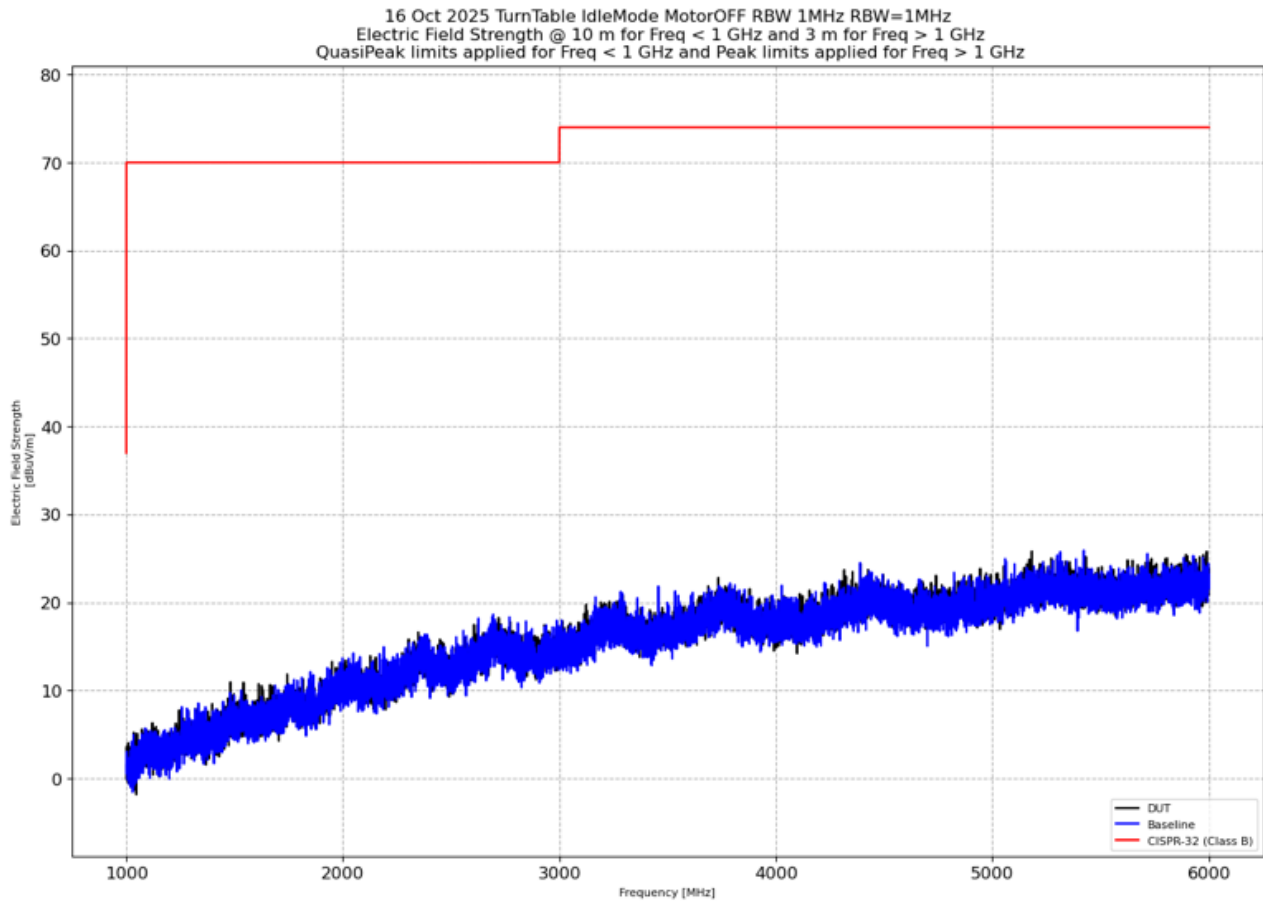


Figure 6.26: ATT Idle mode emissions vs CISPR 32 limits (1 - 6 GHz).

Measurement data for test procedure (6.4.3) section f).

Figure 6.27 & Figure 6.28 shows the radiated emissions test results while the ATT was in running state (motor running). From these Figure 6.27, it can be seen that no significant or distinguishable difference exists between the chamber background (blue trace) and the ATT (black trace) radiated emissions levels over the 50 - 1000 MHz frequency range and it falls well below the CISPR 32 limits.

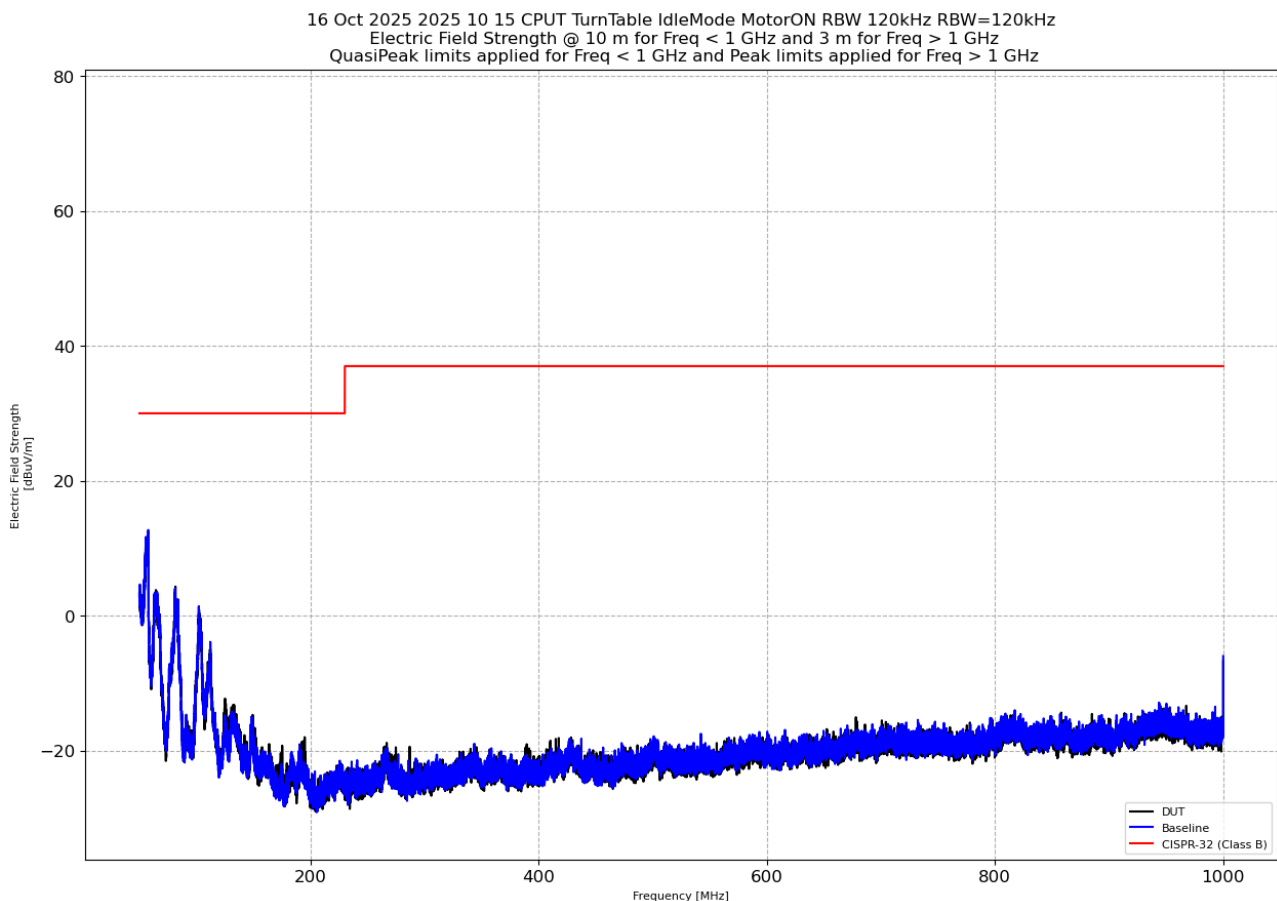


Figure 6.27: ATT running mode emissions vs CISPR 32 limits (50 - 1000 MHz).

Furthermore Figure 6.28 presents the radiated emissions results between 1–6 GHz, and no distinguishable differences are observed in the ATT emissions (black trace) when compared to the chamber background (blue trace). Also when comparing Figure 6.26 with Figure 6.28 no significant difference can be observed between the idle and running states.

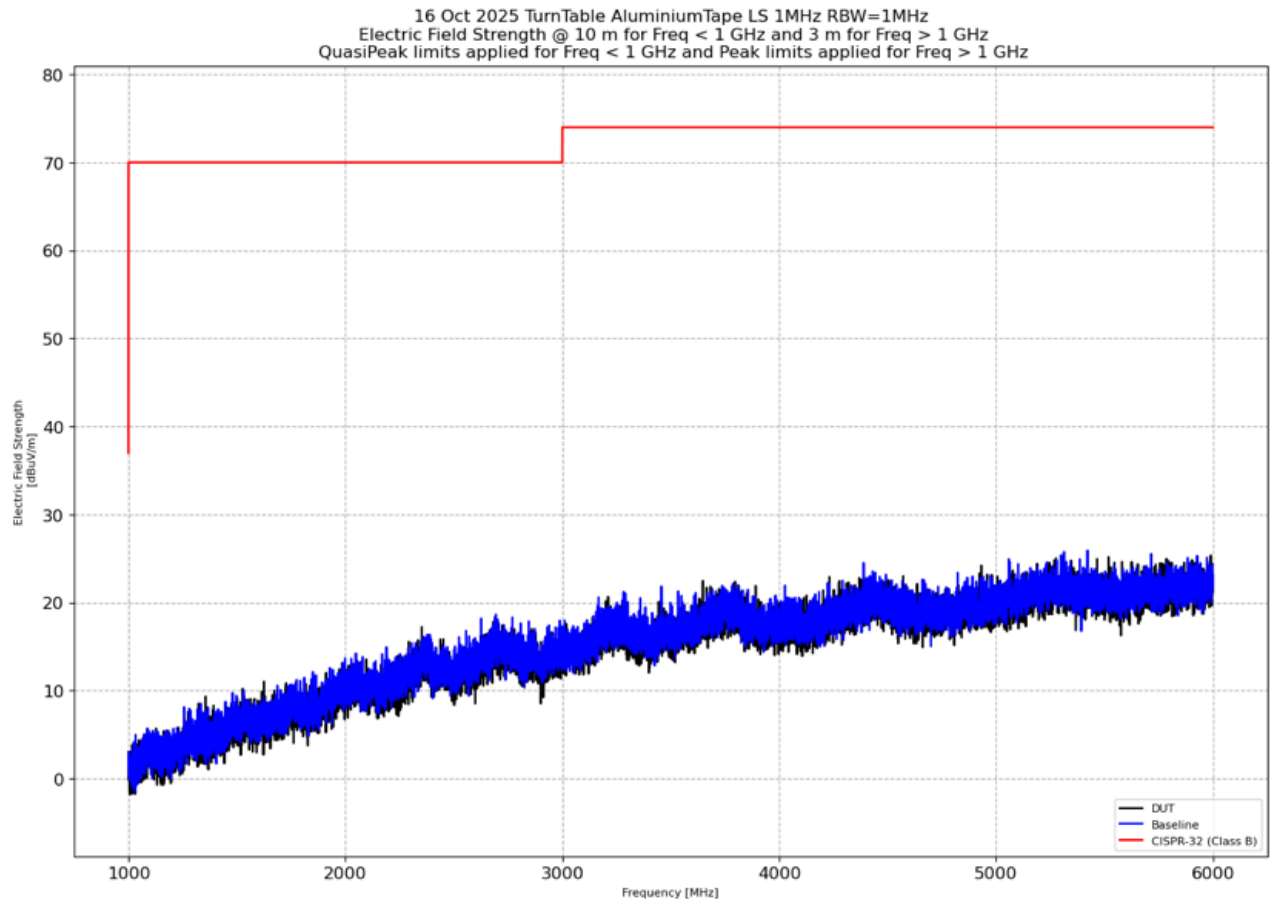


Figure 6.28: ATT running mode emissions vs CISPR 32 limits (1 - 6 GHz).

The radiated emissions measurement results show that the ATT emissions are approximately 30 dB below the CISPR 32 limits across the 50 MHz to 6 GHz frequency range, confirming full compliance with the applicable standard.

6.5 EMC TEST: PULSED RADIATED EMISSIONS

The SARAO RFI team used the DPX (Digital Phosphor) spectrum mode of the Real-Time Spectrum Analyzer (RTSA) to perform pulsed radiated emission measurements. Unlike traditional swept-tuned spectrum analysers, which capture one frequency point at a time, the RTSA processes the entire frequency span in real time, making it particularly effective for detecting short-duration or intermittent emissions. The DPX display visualizes signal activity with colour density, clearly showing the time-varying nature of pulsed emissions. This provides insight into their spectral behaviour and occurrence rate, providing a more accurate assessment of the system's pulsed radiated EMI performance.

6.5.1 REQUIRED TEST EQUIPMENT

The test equipment was the same identical as presented in section 6.4.1

6.5.2 TEST SETUP

The test setup used was the same as presented in Figure 6.22

6.5.3 TEST PROCEDURE

- a) Confirm the setup as in section 6.5.1
- b) Enable the chamber stirrer and LNA
- c) Power the ATT and configure the unit in running mode
- d) Perform a pulsed radiated emissions test using the RTSA in DPX mode with a frequency span : 50 – 1000 MHz
- e) Run test for 2 minutes and confirm if any pulses are observed.

6.5.4 OBSERVATIONS AND RESULTS

The pulsed radiated emissions results is presented in Figure 6.29. No pulsed emissions were observed during the test over the 50MHz to 1GHz, thereby confirming the conclusion of the radiated emission testing.

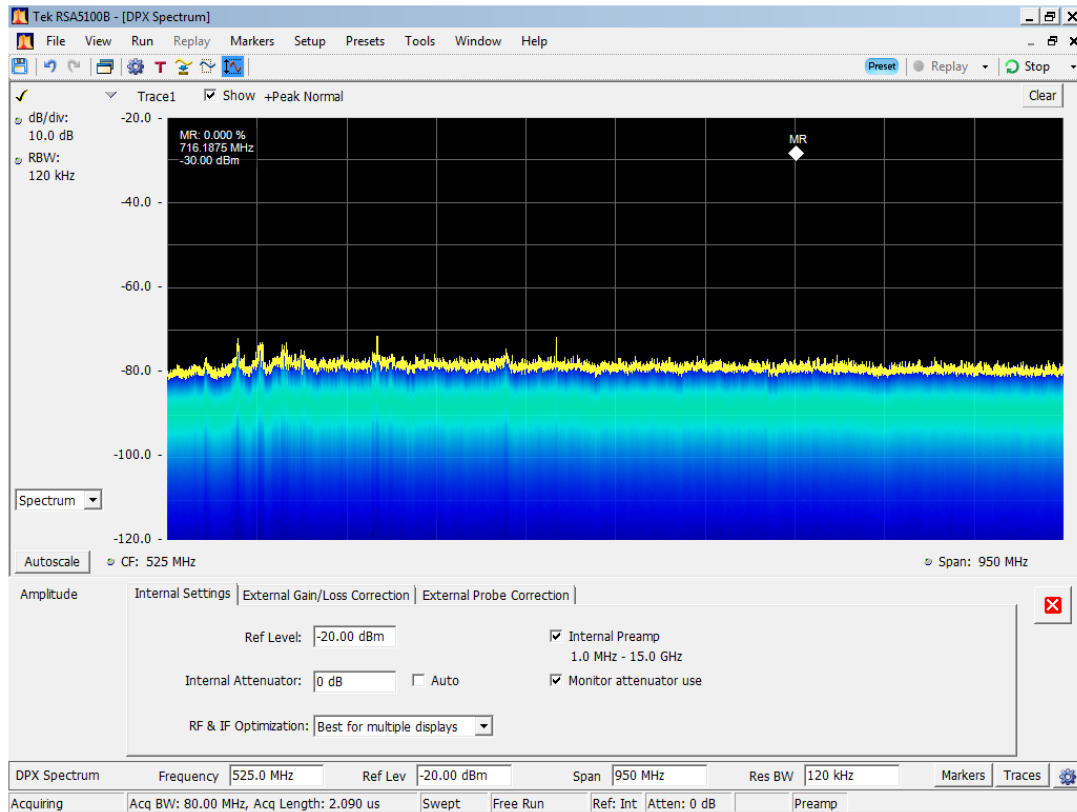


Figure 6.29: Pulsed radiated emissions test result.

6.6 CONCLUSION

This chapter presents evidence that both the design and testing phases successfully confirmed the research objectives outlined in Section 1.3 and the design requirements detailed in Chapter 3 were achieved. The primary goal, “to create a low-emission, shielded, and portable turntable for EMC and antenna testing,” was achieved and validated through functional and EMC testing. Precision and Automation: The ATT provided rotation under a 25 kg load with repeatable angular positioning within $\pm 1^\circ$, thereby fulfilling the rotational requirements. Low Electromagnetic Emissions: Near-field probing indicated up to 30dB attenuation with shielding installed, and common-mode currents stayed below 14 dB μ A. Radiated emissions consistently remained 30 dB below CISPR 32 Class B limits across 50MHz–6 GHz, with no pulsed emissions detected. In conclusion, the ATT proved portable, exhibited low EMI levels, and met international EMC standards, validating the design approach.

CHAPTER 7 CONCLUSION

This research presents a low-cost, low-emission and portable antenna test turntable that was designed, developed and comprehensively tested. This research will aid and enable repeatable, automated antenna and EMC measurements at CPUT, addressing inconsistencies caused by manual setups during antenna and EMC tests.

The conclusion describes how the following objectives defined in Chapter 1 were achieved.

Objective 1: Comprehensive Literature Study

The review of all topics related to the design, development and testing of the ATT were covered. Topics covered included EM and EMC principles, types of EMI source and their coupling mechanisms. EMC standards were studied, and cost-effective EMC pre-compliance test methods. These were limited to near-field probing and common-mode current measurement. Furthermore, compliance level radiated emissions testing was examined, and practical examples were presented. Design techniques for reduced emissions, including shielding, filtering, PCB layout, and fibre-optic communication, were also reviewed. The functional concepts of an ATT were studied, such as motor types, drives and control systems and are presented in 0. The most notable are the practical examples presented from the SKA and MeerKAT radio astronomy projects, and how a reduced radiated emission design was achieved. The literature reviewed was essential to developing and testing a compliant prototype.

Objective 2: Design and Test a Portable, Automated Turntable

A prototype was developed and constructed, the unit was compact, portable and weighed under 15 kg, which makes it suitable for use between test sites as it is easy to setup. The use of COTS components was prioritised. A NEMA 17 stepper motor with a 50:1 gearbox was selected. An EMI-shielded ATmega328p microcontroller system enables communication and provides PWM signal generation for motor control via a motor controller. The power supply system consists of an inline filter, toroidal transformer and a linear PSU. Functional tests performed provided evidence of smooth rotation under a load of 25 kg and angular positioning within $\pm 1^\circ$.

Objective 3: Ensure Shielded Design with Minimal EM/RF Emissions

To meet the reduced-emission requirements, the design implemented multi-layer shielding, EMI-rated connectors, filtered interfaces and fibre-optic communication. The following EMC verification tests confirmed the effectiveness of these measures:

Near-field probing: Emissions were reduced by up to 30 dB with shielding in place and no detectable emissions was observed between running and idle states.

Common-mode currents: A specification 14 dB μ A was achieved for CMC measurements, all the internal and external harnesses of the ATT were measured.

Radiated emissions: Radiated emissions tests conducted at SARA O reverb chamber showed emissions consistently stayed up to 30 dB below CISPR 32 Class B. Measurements were conducted over the 50 MHz–6 GHz span. Additionally, no pulsed emissions were detected.

These results demonstrate that the prototype achieved both precise position feedback and low or negligible EM/RF emissions, fulfilling the design objectives.

Objective 4: Deliver a Cost-Effective Solution

The prototype was constructed at a material cost of ZAR 30,000, significantly lower than commercially available EMC turntables, which typically range between ZAR 120,000 to 250,000. This decrease in cost was primarily achieved by using the COTS component approach, which reduced the need for custom manufacturing of enclosures and low-EMI control and drive systems. Thus, a practical, budget-friendly solution to automated EMC testing is presented.

7.1 RECOMMENDATIONS

Following the design, testing, and evaluation of results, various improvements are suggested. The recommendations will enhance mechanical strength, electromagnetic performance, and positional accuracy.

Custom Electromagnetic Shielded Enclosure

The current modular enclosure approach can be significantly improved with the implementation of a custom multi-cavity enclosure. The custom enclosure should include electromagnetic filter cavities, RFI-gasketed grooves on the seams and lids, EMI-rated fibre-optic feedthroughs, and partitions with filtered feedthroughs accommodation to separate digital and analogue subsystems. The disadvantage of a custom modular enclosure is the high cost associated with manufacturing.

Material Upgrade for Rotating Platform

The MDF rotating platform, provides benefits such as electromagnetically transparent, a good durability, environmental resistance and provides good EM performance (non-conductive), it is also extremely cost-effective. Replacing MDF with engineering plastics like PEEK or Delrin, will add benefits such as chemical resistance, thermal stability and should enhance the mechanical lifespan and environmental resilience. This improvement is generally a cost-effective addition but can depend on the material selected.

Integration of Hall Effect Sensors for Position Feedback

A recommendation to improve angular positioning accuracy can be achieved with the integration of Hall effect sensors into the rotating platform. This will provide real-time magnetic feedback for closed loop control and will allow better repeatability. It will improve calibration and provide fault detection for slippage. The current design makes provision for future closed-loop upgrades with four vacant connection interfaces and MCU pins.

Firmware Enhancements

The current firmware makes provision for PWM motor control and serial communication. To improve reliability, some recommended upgrades include a more structured error reporting scheme that includes detailed fault codes and status messages. The calibration routine can be improved with the implementation of Hall-effect sensors. Lastly, implementing failsafe mechanisms such as emergency stops and timeouts is recommended.

These updates will enhance user-friendliness, ease of maintenance, and suitability for deployment in professional testing environments.

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APPENDIX A

Pin Number	Pin Name	1st Function	2nd Function	3rd Function	Turntable Function Allocation	D-sub Pin
1	PD3	INT1	OC2B	PCINT19	SM Direction control	19
2	PD4	T0	XCK	PCINT20		25
3	GND	—	—	—		14
4	VCC	—	—	—		1
5	GND	—	—	—		18
6	VCC	—	—	—		
7	PB6	XTAL1	TOSC1	PCINT6	USED for external clock	N/A
8	PB7	XTAL2	TOSC2	PCINT7	USED for external clock	N/A
9	PD5	T1	OC0B	PCINT21	Not configured to DSUB	N/A
10	PD6	AIN0	OC0A	PCINT22	Not configured to DSUB	N/A
11	PD7	AIN1	PCINT23	—	Not configured to DSUB	N/A
12	PB0	ICP1	CLKO	PCINT0	Stepper Motor Enable/ fail safe switch	24
13	PB1	OC1A	PCINT1	—	Stepper Motor PWM	12
14	PB2	OC1B	SS	PCINT2	SPARE Input	13
15	PB3	MOSI	OC2A	PCINT3	USED ISP MOSI	7
16	PB4	MISO	PCINT4	—	USED ISP MISO	20
17	PB5	SCK	PCINT5	—	USED ISP sck	8
18	AVCC	—	—	—		
19	ADC6	—	—	—	not used	5
20	AREF	—	—	—		
21	GND	—	—	—		10
22	ADC7	—	—	—	not used	6
23	PC0	ADC0	PCINT8	—	0 Degree position	2
24	PC1	ADC1	PCINT9	—	90 Degree position	15
25	PC2	ADC2	PCINT10	—	180 Degree position	3
26	PC3	ADC3	PCINT11	—	270 Degree Position	16
27	PC4	ADC4	SDA	PCINT12	not used	4
28	PC5	ADC5	SCL	PCINT13	not used	17
29	PC6	RESET	PCINT14	—	nReset	21
30	PD0	RXD	PCINT16	—	UART RXD	22
31	PD1	TXD	PCINT17	—	UART TXD	23
32	PD2	INT0	PCINT18	—	not used	9

APPENDIX B

```
#include <Arduino.h>
#include <EEPROM.h>

#define F_CPU 2000000L
#define pwmPin 9
#define directionPin 3
#define enablePin 8
#define homeSwitchPin 4

// === Motor state variables ===
bool motorRunning = false;
bool rotateCW = true;
int pwmFrequency = 746;

// === Stepper parameters ===
float timePerDegree = 166.7; // ms per 1° rotation

// === Position tracking ===
float currentPosition = 0.0; // degrees

// === Step rotation timing ===
bool stepInProgress = false;
unsigned long stepStartTime = 0;
float stepTargetDegrees = 0;

// =====
// SETUP
// =====

void setup() {
  pinMode(pwmPin, OUTPUT);
  pinMode(directionPin, OUTPUT);
  pinMode(enablePin, OUTPUT);
  pinMode(homeSwitchPin, INPUT_PULLUP);

  digitalWrite(enablePin, LOW);

  // Load saved settings from EEPROM
  EEPROM.get(0, currentPosition);
```

```

if (isnan(currentPosition) || currentPosition < 0 || currentPosition > 360) currentPosition = 0.0;

EEPROM.get(sizeof(currentPosition), pwmFrequency);
if (pwmFrequency < 100 || pwmFrequency > 5000) pwmFrequency = 746;

EEPROM.get(sizeof(currentPosition) + sizeof(pwmFrequency), timePerDegree);
if (timePerDegree <= 0) timePerDegree = 166.7;

configurePWM(pwmFrequency);

Serial.begin(4800);
delay (100);
Serial.println("=== Stepper Ready ===");
Serial.println("Commands: CW, ACW, STOP, CW STEP <deg>, ACW STEP <deg>, FREQ <Hz>,
CALIBRATE, TIME <ms>");
}

// =====
// MAIN LOOP
// =====

void loop() {
  // Serial command handling
  if (Serial.available() > 0) {
    String command = Serial.readStringUntil("\n");
    command.trim();
    command.toUpperCase();

    // --- Continuous rotation CW ---
    if (command == "CW") {
      rotateCW = true;
      digitalWrite(directionPin, LOW);
      digitalWrite(enablePin, HIGH);
      motorRunning = true;
      Serial.println("Motor running CW indefinitely.");
    }

    // --- Continuous rotation ACW ---
    else if (command == "ACW") {
      rotateCW = false;
      digitalWrite(directionPin, HIGH);

```

```

    digitalWrite(enablePin, HIGH);
    motorRunning = true;
    Serial.println("Motor running ACW indefinitely.");
}

// --- Stop motor ---
else if (command == "STOP") {
    stopMotor();
}

// --- Incremental CW STEP ---
else if (command.startsWith("CW STEP ")) {
    float deg = command.substring(8).toFloat();
    if (deg > 0) startStep(deg, true);
    else Serial.println("Invalid step. Use 0-360 deg.");
}

// --- Incremental ACW STEP ---
else if (command.startsWith("ACW STEP ")) {
    float deg = command.substring(9).toFloat();
    if (deg > 0) startStep(deg, false);
    else Serial.println("Invalid step. Use 0-360 deg.");
}

// --- Update PWM frequency ---
else if (command.startsWith("FREQ ")) {
    int freq = command.substring(5).toInt();
    if (freq >= 100 && freq <= 5000) {
        pwmFrequency = freq;
        configurePWM(pwmFrequency);
        EEPROM.put(sizeof(currentPosition), pwmFrequency); // save to EEPROM
        Serial.print("PWM frequency updated to ");
        Serial.println(pwmFrequency);
    } else Serial.println("Invalid frequency. Use 100-5000 Hz.");
}

// --- Set time per degree ---
else if (command.startsWith("TIME ")) {
    float t = command.substring(5).toFloat();
    if (t > 0) {

```

```

        timePerDegree = t;
        EEPROM.put(sizeof(currentPosition) + sizeof(pwmFrequency), timePerDegree); // save to EEPROM
        Serial.print("timePerDegree updated to ");
        Serial.print(timePerDegree);
        Serial.println(" ms/deg.");
    } else Serial.println("Invalid time.");
}

// --- Calibration (limit switch) ---
else if (command == "CALIBRATE") {
    digitalWrite(directionPin, HIGH); // move CCW toward switch
    digitalWrite(enablePin, HIGH);
    motorRunning = true;
    Serial.println("Calibration started. Moving to limit switch...");
}

else Serial.println("Invalid command.");
}

// --- Update step / calibration movements ---
updateStepRotation();
}

// =====
// Step & movement functions
// =====

void startStep(float degrees, bool clockwise) {
    float proposedPosition = currentPosition + (clockwise ? degrees : -degrees);

    if (proposedPosition > 360) degrees = 360 - currentPosition;
    else if (proposedPosition < 0) degrees = currentPosition;

    if (degrees <= 0) {
        Serial.println("Step out of bounds.");
        return;
    }

    stepTargetDegrees = degrees;
    stepStartTime = millis();
    stepInProgress = true;

```

```

rotateCW = clockwise;
digitalWrite(directionPin, clockwise ? LOW : HIGH);
digitalWrite(enablePin, HIGH);
motorRunning = true;

Serial.print("Starting step: ");
Serial.print(degrees);
Serial.println(" deg.");
}

void updateStepRotation() {
    unsigned long elapsed = millis() - stepStartTime;

    // --- Step rotation ---
    if (stepInProgress && elapsed >= stepTargetDegrees * timePerDegree) {
        digitalWrite(enablePin, LOW);
        stepInProgress = false;
        motorRunning = false;

        currentPosition += (rotateCW ? stepTargetDegrees : -stepTargetDegrees);

        // Clamp 0–360°
        if (currentPosition > 360) currentPosition = 360;
        if (currentPosition < 0) currentPosition = 0;

        EEPROM.put(0, currentPosition);

        Serial.print("Step complete. Current position: ");
        Serial.println(currentPosition);
    }

    // --- Calibration (limit switch) ---
    if (digitalRead(homeSwitchPin) == LOW) {
        digitalWrite(enablePin, LOW);
        stepInProgress = false;
        motorRunning = false;
        currentPosition = 0.0;
        EEPROM.put(0, currentPosition);
        Serial.println("Limit switch hit. Calibration complete. 0° set.");
    }
}

```

```

}

// =====
// Stop motor helper
// =====

void stopMotor() {
    digitalWrite(enablePin, LOW);
    motorRunning = false;
    stepInProgress = false;
    Serial.println("Motor stopped.");
}

// =====
// PWM configuration
// =====

void configurePWM(int frequency) {
    int icrValue = (F_CPU / (2 * frequency)) - 1;

    TCCR1A = 0;
    TCCR1B = 0;
    TCCR1A |= (1 << WGM11);
    TCCR1B |= (1 << WGM13) | (1 << WGM12);
    TCCR1B |= (1 << CS10); // no prescaler
    ICR1 = icrValue;
    OCR1A = icrValue / 2; // 50% duty
    TCCR1A |= (1 << COM1A1);
}

```

APPENDIX C

```
import tkinter as tk
from tkinter import ttk, messagebox, scrolledtext
import serial
import serial.tools.list_ports
import threading
import time

class MotorControlGUI:
    def __init__(self, root):
        self.root = root
        self.root.title("Motor Control Interface")
        self.root.geometry("900x550")
        self.root.minsize(850, 500)

        self.serial_port = None
        self.serial_thread = None
        self.running = False

        # ===== UI Elements =====

        # --- Connection frame ---
        conn_frame = ttk.LabelFrame(root, text="Connection", padding=10)
        conn_frame.pack(fill="x", padx=10, pady=5)

        for i in range(7):
            conn_frame.columnconfigure(i, weight=1)

        ttk.Label(conn_frame, text="Port:").grid(row=0, column=0, sticky="w")
        self.port_var = tk.StringVar()
        self.port_menu = ttk.Combobox(conn_frame, textvariable=self.port_var, width=15, state="readonly")
        self.port_menu.grid(row=0, column=1, padx=5)
        self.refresh_ports()

        ttk.Label(conn_frame, text="Baud:").grid(row=0, column=2, sticky="w")
        self.baud_var = tk.StringVar(value="4800")
        ttk.Entry(conn_frame, textvariable=self.baud_var, width=10).grid(row=0, column=3, padx=5)

        self.connect_btn = ttk.Button(conn_frame, text="Connect", command=self.connect_serial)
```

```

self.connect_btn.grid(row=0, column=4, padx=5)
self.disconnect_btn = ttk.Button(conn_frame, text="Disconnect", command=self.disconnect_serial,
state="disabled")
self.disconnect_btn.grid(row=0, column=5, padx=5)
ttk.Button(conn_frame, text="↺", width=3, command=self.refresh_ports).grid(row=0, column=6, padx=5)

# --- Continuous & Step Commands ---
cmd_frame = ttk.LabelFrame(root, text="Motor Commands", padding=10)
cmd_frame.pack(fill="x", padx=10, pady=5)

for i in range(7):
    cmd_frame.columnconfigure(i, weight=1)

# Continuous rotation buttons
ttk.Button(cmd_frame, text="CW", width=12, command=lambda: self.send_command("CW")).grid(row=0,
column=0, padx=3, pady=3, sticky="ew")
ttk.Button(cmd_frame, text="ACW", width=12, command=lambda: self.send_command("ACW")).grid(row=0,
column=1, padx=3, pady=3, sticky="ew")
ttk.Button(cmd_frame, text="STOP", width=12, command=lambda:
self.send_command("STOP")).grid(row=0, column=2, padx=3, pady=3, sticky="ew")

# Step rotation
ttk.Label(cmd_frame, text="Step (deg):").grid(row=0, column=3, sticky="e", padx=3)
self.step_var = tk.StringVar(value="10")
ttk.Entry(cmd_frame, textvariable=self.step_var, width=8).grid(row=0, column=4)
ttk.Button(cmd_frame, text="CW STEP", width=12, command=self.send_cw_step).grid(row=0, column=5,
padx=2, sticky="ew")
ttk.Button(cmd_frame, text="ACW STEP", width=12, command=self.send_acw_step).grid(row=0, column=6,
padx=2, sticky="ew")

# PWM frequency
ttk.Label(cmd_frame, text="FREQ (Hz):").grid(row=1, column=0, sticky="e", padx=3)
self.freq_var = tk.StringVar(value="1333")
ttk.Entry(cmd_frame, textvariable=self.freq_var, width=10).grid(row=1, column=1)
ttk.Button(cmd_frame, text="Send FREQ", width=12, command=self.send_freq).grid(row=1, column=2,
padx=3, sticky="ew")

# Time per degree
ttk.Label(cmd_frame, text="TIME (ms/deg):").grid(row=1, column=3, sticky="e", padx=3)
self.time_var = tk.StringVar(value="166.7")

```

```

    ttk.Entry(cmd_frame, textvariable=self.time_var, width=10).grid(row=1, column=4)
    ttk.Button(cmd_frame, text="Send TIME", width=12, command=self.send_time).grid(row=1, column=5,
padx=3, sticky="ew")

# Home & Calibrate
    ttk.Button(cmd_frame, text="HOME", width=12, command=lambda:
self.send_command("HOME")).grid(row=2, column=0, padx=3, pady=3, sticky="ew")
    ttk.Button(cmd_frame, text="CALIBRATE", width=12, command=lambda:
self.send_command("CALIBRATE")).grid(row=2, column=1, padx=3, pady=3, sticky="ew")

# --- Custom command ---
    custom_frame = ttk.LabelFrame(root, text="Custom Command", padding=10)
    custom_frame.pack(fill="x", padx=10, pady=5)
    custom_frame.columnconfigure(0, weight=3)
    custom_frame.columnconfigure(1, weight=1)

    self.custom_var = tk.StringVar()
    ttk.Entry(custom_frame, textvariable=self.custom_var).grid(row=0, column=0, padx=5, sticky="ew")
    ttk.Button(custom_frame, text="Send", width=12, command=self.send_custom).grid(row=0, column=1,
padx=5, sticky="ew")

# --- Log output ---
    log_frame = ttk.LabelFrame(root, text="Serial Log", padding=10)
    log_frame.pack(fill="both", expand=True, padx=10, pady=5)
    log_frame.columnconfigure(0, weight=1)
    log_frame.rowconfigure(0, weight=1)

    self.log_area = scrolledtext.ScrolledText(log_frame, wrap=tk.WORD, height=15, state='disabled')
    self.log_area.grid(row=0, column=0, sticky="nsew")

# ----- Serial functions -----
def refresh_ports(self):
    ports = [port.device for port in serial.tools.list_ports.comports()]
    self.port_menu['values'] = ports
    if ports: self.port_menu.current(0)
    else: self.port_menu.set("")

def connect_serial(self):
    port = self.port_var.get()
    baud = self.baud_var.get()

```

```

if not port:
    messagebox.showerror("Error", "No COM port selected.")
    return
try:
    self.serial_port = serial.Serial(port, baudrate=int(baud), timeout=0.5)
    self.running = True
    self.serial_thread = threading.Thread(target=self.read_serial, daemon=True)
    self.serial_thread.start()
    self.connect_btn.config(state="disabled")
    self.disconnect_btn.config(state="normal")
    self.log("Connected to " + port)
except Exception as e:
    messagebox.showerror("Connection Error", str(e))

def disconnect_serial(self):
    self.running = False
    if self.serial_port and self.serial_port.is_open:
        self.serial_port.close()
    self.connect_btn.config(state="normal")
    self.disconnect_btn.config(state="disabled")
    self.log("Disconnected.")

def read_serial(self):
    while self.running and self.serial_port and self.serial_port.is_open:
        try:
            data = self.serial_port.readline().decode(errors='ignore').strip()
            if data:
                self.log(data)
        except Exception:
            break
        time.sleep(0.05)

# ----- Command senders -----
def send_command(self, cmd):
    if not self.serial_port or not self.serial_port.is_open:
        messagebox.showwarning("Not Connected", "Connect to a serial port first.")
        return
    self.serial_port.write((cmd + '\n').encode())
    self.log(">> " + cmd)

```

```

def send_freq(self):
    try:
        freq = int(self.freq_var.get())
        self.send_command(f"FREQ {freq}")
    except ValueError:
        messagebox.showerror("Invalid Input", "Enter a valid integer frequency.")

def send_time(self):
    try:
        t = float(self.time_var.get())
        self.send_command(f"TIME {t}")
    except ValueError:
        messagebox.showerror("Invalid Input", "Enter a valid number.")

def send_cw_step(self):
    try:
        deg = float(self.step_var.get())
        self.send_command(f"CW STEP {deg}")
    except ValueError:
        messagebox.showerror("Invalid Input", "Enter a valid degree value.")

def send_acw_step(self):
    try:
        deg = float(self.step_var.get())
        self.send_command(f"ACW STEP {deg}")
    except ValueError:
        messagebox.showerror("Invalid Input", "Enter a valid degree value.")

def send_custom(self):
    cmd = self.custom_var.get().strip()
    if cmd:
        self.send_command(cmd)
        self.custom_var.set("")

# ----- Logging -----
def log(self, message):
    self.log_area.config(state='normal')
    self.log_area.insert(tk.END, message + "\n")
    self.log_area.config(state='disabled')
    self.log_area.yview(tk.END)

```

```
# ===== Main =====  
if __name__ == "__main__":  
    root = tk.Tk()  
    app = MotorControlGUI(root)  
    root.mainloop()
```