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# Reverberation Chamber Test System for Antenna Measurements

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## Abstract

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The objectives of this thesis work were to implement the RTS60 Reverberation Test System for use at GE Healthcare Finland Oy and develop a CLI based control program for the reverberation chamber. The test system is used by the company for conducting OTA measurements, such as antenna efficiency and total radiated power evaluations on wireless devices. Due to the modular architecture of Python script, additional features can be included to the control program in the future.

For the implementation of the test system control program, some reverse engineering of the reverberation chamber was necessary to understand its operational mechanism. The control program was developed based on the data obtained from the reverse engineering of the RTS60 reverberation chamber. Finally, antenna efficiency and total radiated power measurements were conducted with the RTS60 test system and control program.

The test system and its control program were found to be functional based on the analysis of the measurement results.

Keywords: Reverberation chamber, Antenna efficiency, Total radiated power

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Tämän opinnäytetyön tavoitteina oli ottaa RTS60-testijärjestelmä käyttöön GE Healthcare Finland Oy:lle sekä kehittää CLI-pohjainen testiohjelma heijastuskammion ohjaukseen. Yritys käyttää testijärjestelmää langattomien laitteiden OTA-mittauksiin, kuten antennin hyötysuhteen sekä laitteen kokonaissäteilytehon arviointeihin. Testiohjelmaan voidaan tulevaisuudessa lisätä uusia ominaisuuksia Python-koodin modulaarisen arkkitehtuurin vuoksi.

Testiohjelman toteuttamiseen vaadittiin hieman käänteistä suunnittelua, jotta heijastuskammion toimintamekanismia opittiin ymmärtämään. Testiohjelma kehitettiin käyttäen hyväksi käänteisestä suunnittelusta saatua tietoa. Lopuksi RTS60-testijärjestelmällä ja siihen luodulla testiohjelmalla suoritettiin antennin hyötysuhde- sekä kokonaissäteilytehomittaukset.

Testijärjestelmä ja sen testiohjelma osoittautuivat toimiviksi mittaustulosten analysoinnin perusteella.

Avainsanat: heijastuskammio, antennin hyötysuhde, kokonaissäteilyteho

## Contents

1	Introduction	1
2	Reverberation Chamber	2
2.1	Background	2
2.2	Operating Principles	3
2.3	Field Distribution	4
2.4	Mode Stirring	5
2.4.1	Stepped-mode	5
2.4.2	Continuous Stirred Mode	6
2.5	Reciprocity	6
2.6	Reverberation Chamber vs Anechoic Chamber	7
2.7	RTS60 Reverberation Test System	7
3	Reverse Engineering of the Chamber	8
3.1	RTS60 Operation	8
3.2	Signal Sniffing Setup	9
3.3	Sniffing the Signals	10
4	Test System Control Program	13
4.1	Integration and Control Components	13
4.1.1	SCPI Commands	13
4.1.2	Virtual Instrument Software Architecture	13
4.1.3	Python Packages	14
4.1.4	Flag Variable	14
4.2	Motion Controller Commands	14
4.3	Control Program Implementation	16
4.3.1	Chamber Initialization	16
4.3.2	Motor Control	18
4.3.3	Integration of Power Monitoring	20
4.3.4	Test Script	21
5	Antenna Efficiency and Total Radiated Power Measurements	23
5.1	The Setup	23
5.2	Reference Measurement	24
5.3	Antenna Efficiency Measurement	25

5.4	Total Radiated Power Measurement	26
6	Measurement Results and Analysis	27
6.1	Chamber Path Loss and Stabilization	27
6.2	Antenna Efficiency	29
6.3	Total Radiated Power	30
7	Conclusion	32
	References	34

## List of Abbreviations

AC	Anechoic chamber
AE	Antenna efficiency
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
CLI	Command-line interface
dB	Decibel
dBm	Decibel-milliwatts
DUT	Device under test
EM	Electromagnetic
EMC	Electromagnetic compatibility
mW	Milliwatt
OTA	Over-the-Air
PC	Personal computer
RC	Reverberation chamber
RF	Radio frequency
STD	Standard deviation

TRP	Total radiated power
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
W	Watt

# 1 Introduction

As various radio wave-based technologies have become part of daily life, ensuring the reliability and performance of radio devices in diverse electromagnetic (EM) environments has become crucial. To ensure that devices work well together without causing EM interference issues, testing must be done thoroughly to understand how antennas and radio systems perform. The electromagnetic reverberation chamber is a versatile and dynamic testing environment for achieving these objectives.

Reverberation chamber (RC) offers an alternative way of EM testing compared to more traditional measurement methods, such as anechoic chamber (AC). They exploit mode stirring to create a statistically uniform and isotropic EM fields, providing an environment capable of simulating a complex real-world EM scenario. This feature has become invaluable for evaluating electromagnetic compatibility (EMC), antenna performance, and wireless communication device testing.

One of the purposes of this thesis is to familiarize the reader with RCs by briefly telling about chamber's background, and explaining the theory, operation principles, and design of the RC. RTS60 reverberation test system is the chamber utilized for the thesis.

In addition to coherently looking into the fundamental aspects of reverberation chambers, this thesis is going to explain in chronological order how the test system was reverse engineered and command-line interface (CLI) based control program implemented.

Lastly, the measurement setup will be explained, and measurements conducted and analyzed with the test system to demonstrate the effectiveness of reverberation chambers. Readers are assumed to have a basic understanding of programming and radio frequency (RF) engineering.

## 2 Reverberation Chamber

In the field of EMC (electromagnetic compatibility) testing and antenna characterization, diverse tools and techniques are used to evaluate the performance of the DUT (device under test). One such tool is the electromagnetic RC, that is extensively utilized across industries to test EM characteristics of equipment.

### 2.1 Background

An electromagnetic reverberation chamber, also known simply as a reverberation chamber or a mode-stirred chamber is a testing facility that was first proposed in 1968 for EMC measurements by Mendes, H.A [1].

RC was a target of scepticism at first due to various reasons, such as lack of information, unanswered questions concerning the accuracy of the measurement results, and the absence of evident connection between test outcomes with other more traditional measurement methods, such as anechoic chamber measurements. [2.]

RCs have been enjoying growing popularity as a promising test facility past decades and are considered as a time efficient, small space and cost-effective way of performing different EM measurements. In addition to EMC measurements, RCs are now used more extensively for antenna performance and wireless systems Over-the-Air (OTA) measurements, such as MIMO (multiple-input and multiple-output) devices performance evaluation. [3; 4.]

## 2.2 Operating Principles

The reverberation chamber is typically a rectangular-shaped and electrically large enclosure with a high-quality factor. RCs are designed to simulate a real-world environment for electromagnetic measurements of a DUT (device under test). [2.] Figure 1 presents one method of implementing a RC.

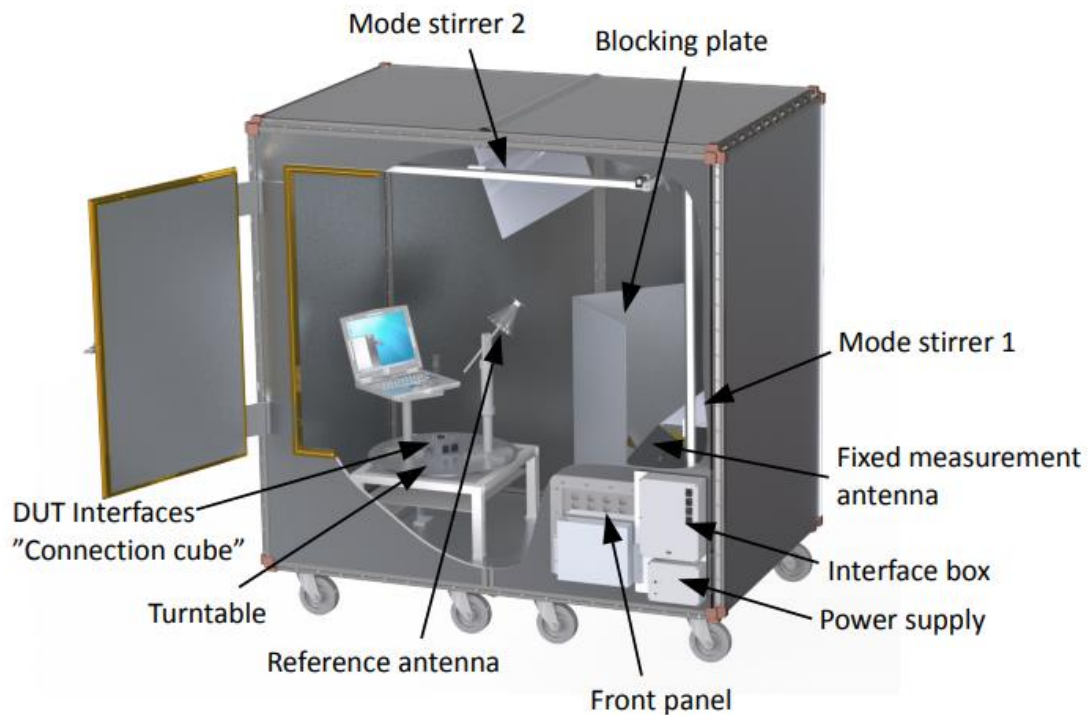


Figure 1. Bluetest RTS60 reverberation chamber. [5]

The mode stirrers are metal objects of different shapes and movement trajectories that are used to stir the EM fields inside the RC. By mechanically moving the stirrers, the boundary conditions inside RC are continuously and randomly altered. That leads to resonant and non-resonant modes changing, thus creating a complex and chaotic EM environment within the chamber when excited with EM energy via the DUT or reference antenna. [6.]

As the chamber is excited and the mode stirrers move through a range of different positions, the EM fields evolve over time, and by averaging over a sufficient number of stirrer positions, the EM field distribution can be considered

statistically uniform (time averaged) and isotropic within the usable working volume. [7.]

Highly reflective walls of the RC enable the DUT to be exposed to EM waves from all angles and polarizations. [7.]

While not necessary for RCs functionality, some models include additional equipment mounted inside, such as a turntable that is used to change the coupling between the DUT and the chamber, and a blocking plate to prevent line-of-sight radiation between fixed antennas and the DUT. [6.] These features further reduce standing waves and will enhance the uniformity of fields, leading to even more consistent field distribution.

### 2.3 Field Distribution

Within a RC, the EM field distribution is characterized by a standing-wave pattern resulting from reflections off the chamber walls. According to electromagnetic theory, within these fields exists various resonant modes, each representing a specific spatial pattern of the standing-wave distribution in the EM field. The overall field inside the chamber is the summation of these resonant modes. [8.] Figure 2 illustrates the EM field distribution in a RC.

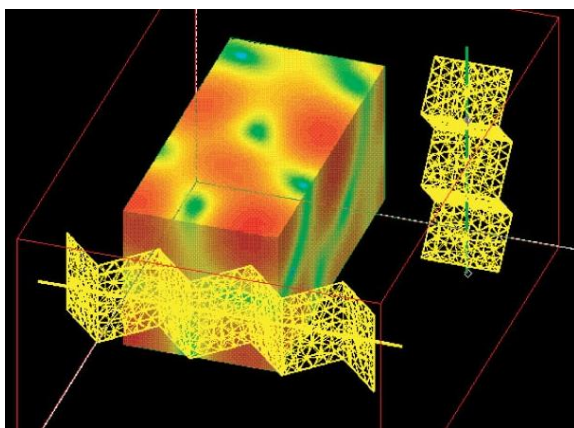


Figure 2. Field distribution within a RC. [8]

The standing-wave pattern inside a RC is directly affected by the boundary conditions of the chamber, therefore by altering these conditions, the EM fields throughout the working volume fluctuate. This altering is implemented by a process known as mode stirring, which aims to expose every position within the chamber to similar maximum, minimum and average EM field strengths. Once this statistical uniformity is achieved, the chamber is referred to as well-stirred, and considered suitable for EM testing. [8.]

## 2.4 Mode Stirring

Mode stirring in a RC refers to mechanically rotating or moving the stirrers to alter the boundary conditions inside the chamber. The primary goal of mode stirring is to prevent dominant resonant modes that lead to standing waves and therefore uneven field distribution. Mode stirring helps to achieve a more homogeneous and isotropic EM field by redistributing it with the stirrers.

There are different ways of implementing the mode stirring, but two of the most common methods are a stepped-mode and continuously stirred modes.

### 2.4.1 Stepped-mode

In a stepped operation, the stirrer or multiple stirrers are set at specific positions or rotational angles during measurements. This fixed positioning ensures a consistent EM field exposure for the DUT over any desired duration. However, the process of halting the stirrer for each measurement extends the overall measurement time. Additionally, the initiation and halting of stirrer movement generates mechanical vibrations, potentially causing a 'crackling' effect that can introduce significant transients in the field. Measurements must be delayed until these mechanically induced transients diminish. [7.]

Due to the prolonged measurement time associated with the stepped approach, industry standards allow for the use of as few as 12 distinct stirrer positions in qualification testing. This limitation results in products being qualified with tests

that expose the DUT to a restricted number of aspect angles and polarizations, consequently increasing the variance of the measurements. [7.]

#### 2.4.2 Continuous Stirred Mode

Continuous stirring is an alternative methodology of implementing mode stirring. In this method, the stirrer undergoes continuous rotation/movement during the measurements, without halting at specific angles or positions. This approach offers a significant reduction in testing time compared to the stepped method, making it a time-efficient solution. Furthermore, the continuous stirring eliminates the crackling effect associated with mechanical backlash during the stirrers start and stop sequences. Unlike the stepped-mode, continuous stirring avoids acceleration issues once the stirrer achieves its desired movement/rotation speed. [7.]

Continuous stirring is advantageous compared to the stepped mode, as it exposes the DUT to maximum possible field configurations within the RC when the stirrer completes a full round at the operating frequency. However, there is a concern involved with continuous stirring susceptibility testing, that the DUT may potentially not be exposed to the required EM field strength for an adequate duration to achieve trustworthy measurement results. [7.]

#### 2.5 Reciprocity

RCs were at first mostly used for radiated immunity/susceptibility testing, but due to their reciprocity, chambers are equally applicable for radiated emission testing of the DUT. [3.] Reverberation chamber being a reciprocal environment refer to EM fields within chamber behave the same regardless of EM waves direction. In simpler terms, the chambers response will be same whether waves are being emitted or received by the DUT.

## 2.6 Reverberation Chamber vs Anechoic Chamber

The fundamental difference between an AC and a RC lies in their basic functionality, which could be described as opposite. While the walls inside an AC are fully covered with absorbers to eliminate any reflections within the chamber, in the case of a RC the walls are designed to be as highly reflective as possible to create a complex EM environment.

ACs are ideal for precise antenna characterization, while RCs are simpler, faster, and more cost-efficient test systems. However, there are some disadvantages in RCs compared to ACs, such as the loss of information regarding radiation pattern and polarization due to reflections. [9.]

Each chamber has its own advantages and limitations, and they can be considered as complementary tools in EM testing and measurement.

## 2.7 RTS60 Reverberation Test System

The RTS60 reverberation test system, manufactured by Bluetest, is the RC used for this thesis work. Capable of performing both passive and active measurements, The RTS60 can assess parameters such as antenna efficiency, diversity and MIMO gain, total radiated power (TRP), total isotropic sensitivity (TIS) and throughput (TPUT) [4].

Bluetest guarantees an accuracy of 0.3 dB (STD) and repeatability of 0.1 dB (STD) for measurements conducted with the RTS60, with a test time of only one minute for each measurement. RTS60 provides a wide frequency range of 650 – 6000 MHz for the measurements. [4.]

This model consists of two mode stirrers, a turntable, a blocking plate, and both reference and fixed measurement antennas.

### 3 Reverse Engineering of the Chamber

To understand the operational mechanism of the RTS60, some reverse engineering had to be done. This involved dismantling the RC to learn about its functioning and sniffing the control signals transmitted by the measurement software, developed by Bluetest.

#### 3.1 RTS60 Operation

First, the chamber was dismantled to understand better how the original measurement software (Bluetest Measurement Suite) controls the test system. The RTS60 contains three motors that control the vertical and horizontal mode stirrers, and the turntable. Triple Axis Microstepping Motion Controller, manufactured by Simple Step, is used for communication between the control PC (personal computer) and three motors within The RTS60.

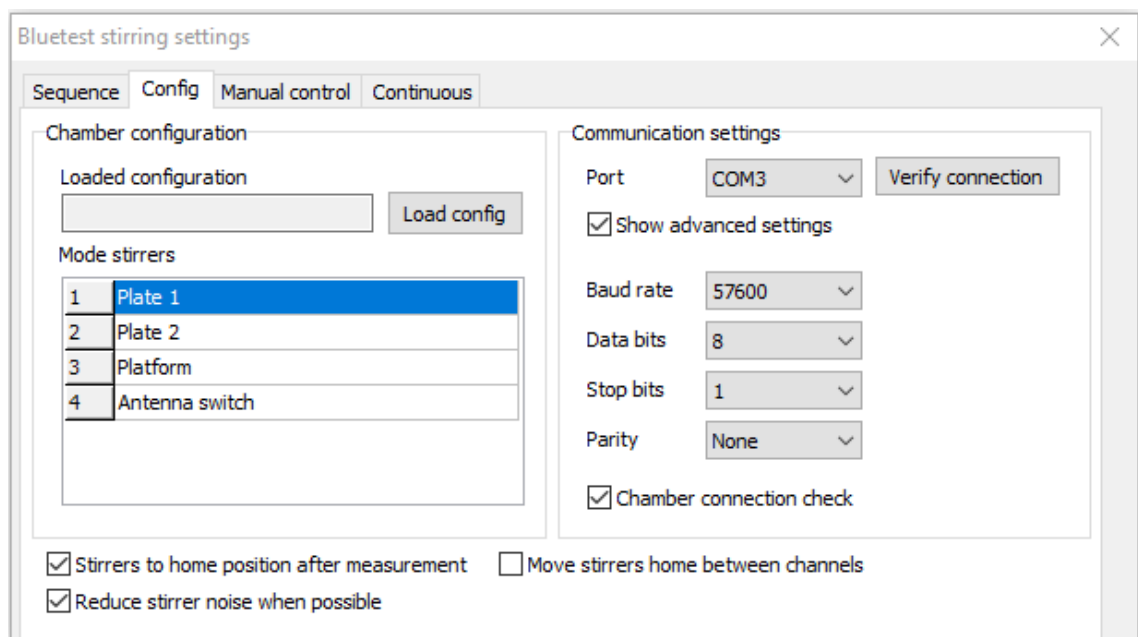


Figure 3. Serial communication settings.

Transmission of data in between the motion controller and the control PC utilizes RS-232 serial communication standard. The serial communication between devices is configured with a baud rate of 57600, eight data bits, one

stop bit, and no parity bit. Figure 3 presents configuration settings view in Bluetest Measurement Suite.

### 3.2 Signal Sniffing Setup

To create the test system control program, a custom RS-232 cable had to be made for sniffing the control signals. RS-232 cable was cut in half and then soldered back together with additional wires added to access the UART (Universal Asynchronous Receiver Transmitter) signal traffic. Figure 4 presents the customized cable, clearly showing the separated TXD (transmit data), RXD (receive data) and GND (ground) wires.

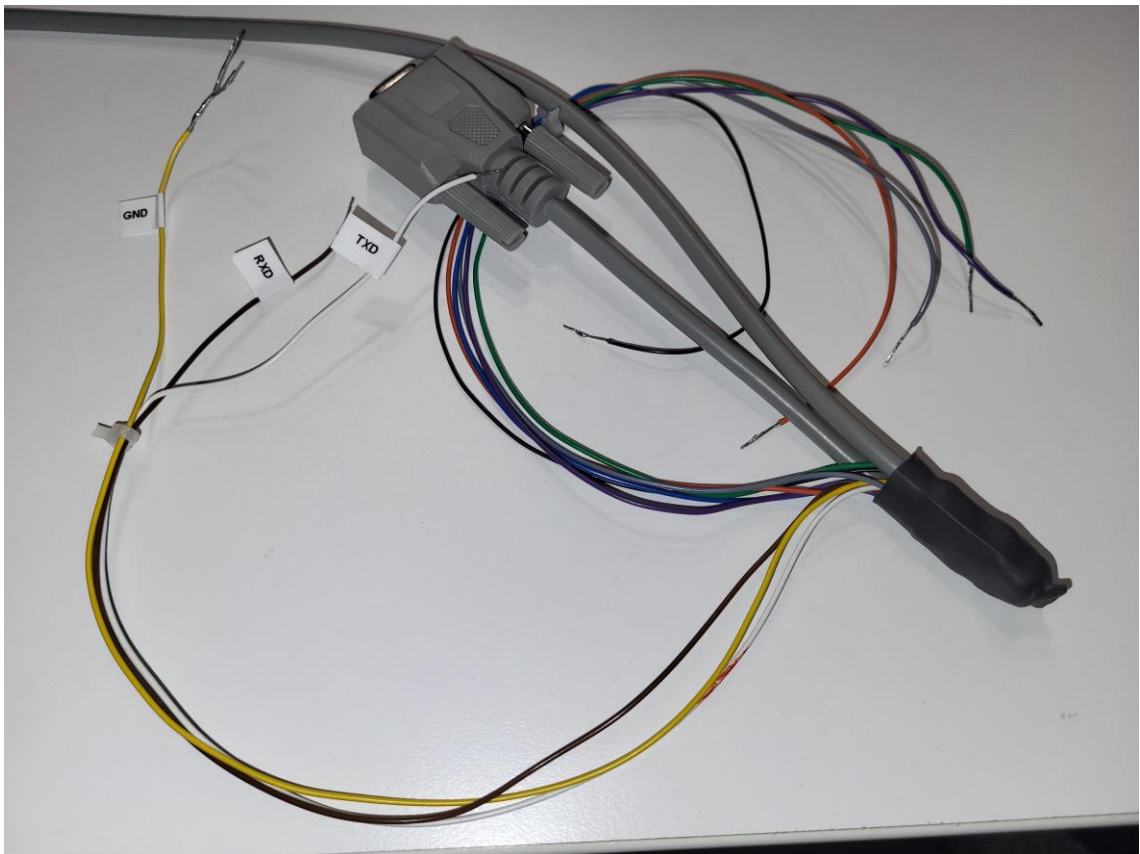


Figure 4. Customized RS-232 cable for UART signal sniffing.

In the control signal sniffing setup, due to lack of RS-232 port in control computer, RS-232 to USB (Universal Serial Bus) converter had to be used. The

custom RS-232 cable was connected to the RTS60 and then to the control PC via the adapter.

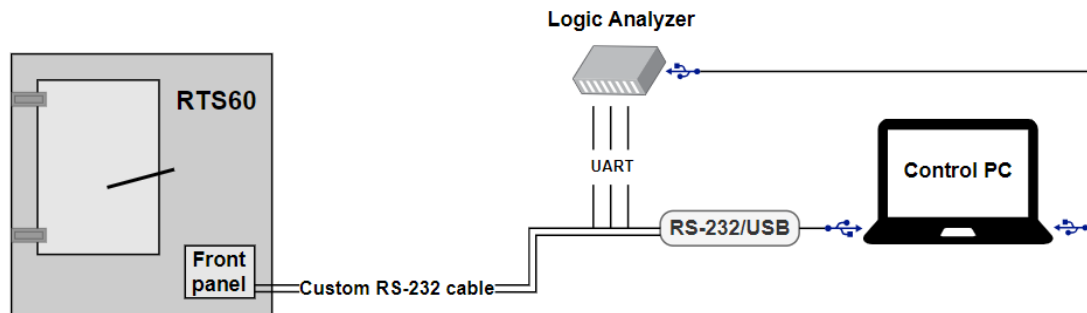


Figure 5. Block Diagram of UART signal sniffing setup.

The added wires of the custom cable were connected to the logic analyzer for UART traffic sniffing. Full sniffing setup is illustrated in figure 5.

### 3.3 Sniffing the Signals

While the logic analyzer monitored the UART signals of the RS-232 cable for serial communication sequences, the RTS60 was controlled using the Bluetest Measurement Suite. Figure 6 presents the manual control window within the Bluetest measurement Suite.

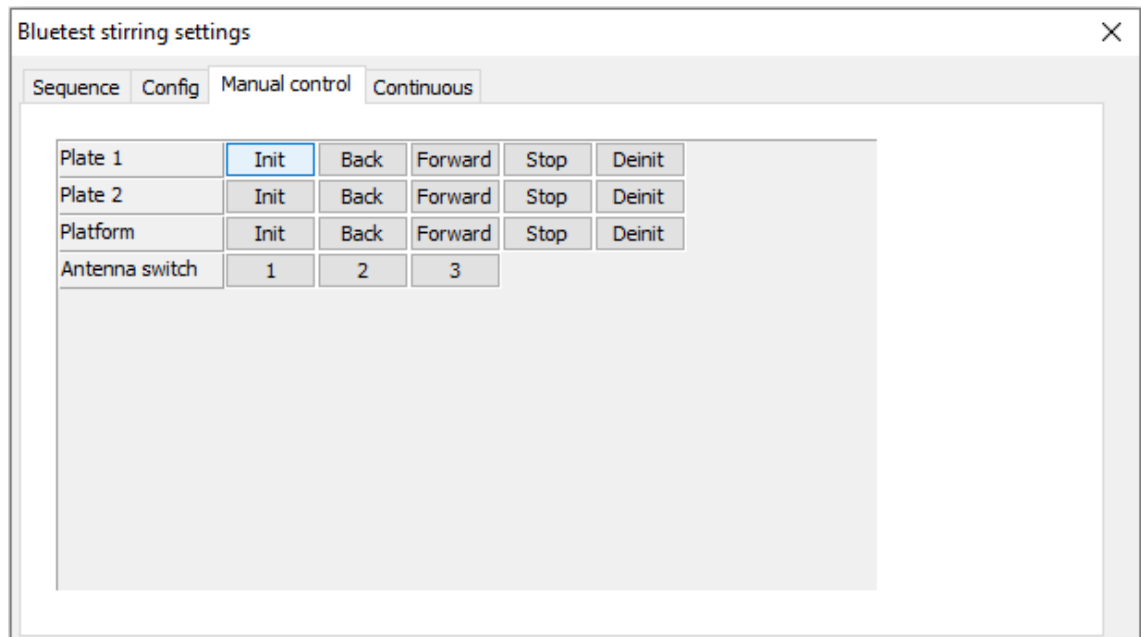


Figure 6. Manual control window of the Bluetest Measurement Suite.

Executing a manual control command with the Measurement Suite sends a serial data sequence to the motion controller and the motion controller sends back its response about motor state.



Figure 7. Sniffed serial data.

In figure 7, the data communication between the control PC and the motion controller can be seen after pressing Init (Initialize) button in the Measurement Suite. The Logic Pro 16 analyzer is employed for capturing, while the Logic

(application) is utilized for interpreting the serial data. Both tools are manufactured by Saleae.

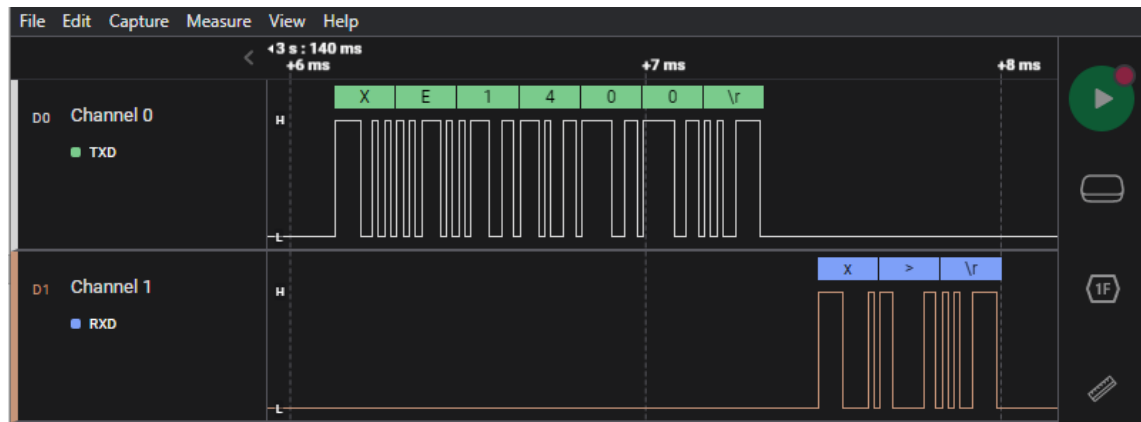


Figure 8. Zoomed look of the transmitted command and response from the motion controller.

Figure 8 presents a closer look of UART communication between the control PC and the motion controller, presented as ASCII (American Standard Code for Information Interchange) characters. Serial data sequence 'XE1400\r' is sent from the control PC, meaning that X-axis of the motion controller is targeted (X), end velocity of the motor is set to 1400 steps per second (E1400), followed by carriage return (\r). Motion controller then sends back 'x>\r', which stands for the response from X-axis (x), system is ready for another command (>) and carriage return (\r).

All the manual control buttons of the Measurement Suite were pressed for Plate 1 (vertical motion stirrer), Plate 2 (horizontal motion stirrer) and Platform (turntable) to collect the serial data for motor directions, motor positions and other essential settings that are used to control the motors.

## 4 Test System Control Program

To write the test system control program, previously captured UART signals are utilized in the program for the chamber control. Additionally, understanding and utilizing the SCPI commands is necessary for integrating the NRQ6 power meter into the Python script and synchronize its operation with the RC.

### 4.1 Integration and Control Components

Components presented in chapter 4.1 are used to facilitate communication and control between the RC, measurement devices and the control PC, as well as ensuring smooth flow within the program.

#### 4.1.1 SCPI Commands

SCPI (Standard Commands for Programmable Instruments), also known and pronounced as a “skippy” is a syntax included in IEEE 488.2 standard that specifies a common command structure and data formats to be used as communication instructions between the host device and the instrument. As the commands are presented as ASCII string format, SCPI instruction set is very user friendly, and they are easily readable by individuals without specialized backgrounds. [10.]

Using the SCPI instruction set provides a great compatibility between devices. Since it does not define the physical layer implementation method, it can be used with many different hardware buses such as RS-232, RS-422, Ethernet and USB. [10.]

#### 4.1.2 Virtual Instrument Software Architecture

VISA (Virtual Instrument Software Architecture) is a standardized communication API (Application Programming Interface) that is widely used with test and measurement devices. It provides for the development of programs to be hardware bus independent and is often referred as a communication driver.

VISA libraries allow programs to communicate with diverse interfaces, including GPIB, USB and Ethernet. [11.]

### 4.1.3 Python Packages

In order to control the test system with Python, some Python packages are required to be imported to the script.

*pyVISA* is a Python package for VISA support to control the NRQ6 power meter via USB.

*pyserial* encapsulates the access for the serial port, providing backends for Python operating on Windows. It is an essential package for serial data communication through Python.

*argparse* is a package that provides a parser for command-line arguments.

*time* module provides time-related functions for delays in the Python script.

*math* is a module that contains simple mathematical functions, such as logarithms for watt to dBm (decibel-milliwatts) conversion.

### 4.1.4 Flag Variable

In programming, a 'flag' typically refers to a Boolean variable used to indicate a status or a state. Flags are commonly used to control the flow of a program execution, to signal the occurrence of certain events and provide information of a state of something.

## 4.2 Motion Controller Commands

Commanding the Simple Step Motion Controller is carried out by using simple ASCII commands, with values typically indicating the step count or steps per

second. Specific axis of the motion controller and therefore motor are addressed by using a prefix at the front of each motion controller command.

Table 1. Prefix characters for motor addressing.

Motor	Prefix character from the control PC	Prefix character from the motion controller
X-axis	X	x
Y-axis	Y	y
Z-axis	Z	z

After a prefix, the command is appended with an appropriate value, followed by a carriage return to indicate ending of the command. Below is an example command sent by the control PC to the motion controller.

*XM12000r*

In the example command, the X-axis is addressed, instructing the corresponding motor to move to an absolute position of 12000 steps.

Table 2. Commands from the control PC to the motion controller.

Command	Description
H	Set motor to half step
B	Set beginning velocity
E	Set end velocity
S	Set slope
P	Set power settings
N	Direction of the motor movement
M	Move motor to absolute position
m	Ask for current motor position
!	Stop motor

After motion controller has received the command, it will proceed to transmit its response back to the control PC.

*xb\r*

In the provided example is the motion controller's response for the movement command, indicating that the motor of the X-axis is currently running.

Table 3. Responses from the motion controller to the control PC.

Response	Description
>	System is ready for another command
b	Motor is running
H	Motor at Home position, cannot move past home
L	Motor at Limit position, cannot move past limit
a	Motor abort in progress

While Simple Step Motion Controllers offer a wide range of functionalities and commands, many of them are not relevant to the specific needs for controlling the RC. Tables 1, 2 and 3 outline the prefixes, commands and responses utilized by the control program.

### 4.3 Control Program Implementation

The test system control program was developed by using the Python programming language, chosen for its simplicity and versatility. The script was designed to be modular architecture, so that additional functions beyond the antenna efficiency (AE) and total radiated power (TRP) measurements can be conveniently added in the future.

#### 4.3.1 Chamber Initialization

Prior to using, the RC requires initialization to configure the correct settings for the motors controlling the movement of the stirrers and turntable. These initialization settings were sniffed beforehand, therefore the settings used in the control program are identical to the initialization settings used by the Bluetest Measurement Suite.

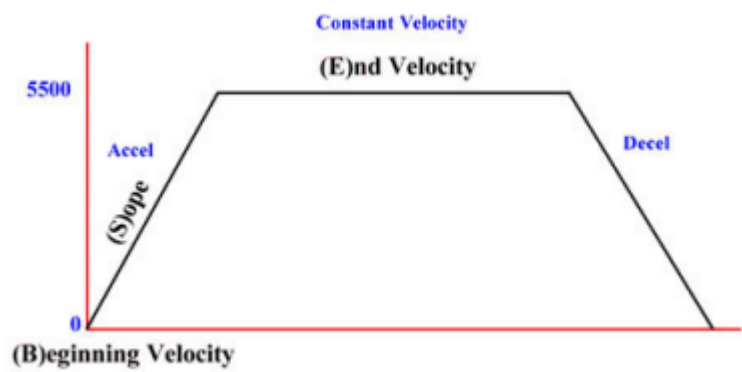


Figure 9. Speed setting profile of the motors. [12]

Reverberation chamber initialization involves setting up the speed settings for the motors. The velocity profile of the motor during a typical travel interval is shown in figure 9. There are three distinct components that determine how fast the stirrers and turntable are moving inside the chamber. Beginning and end velocities define the startup speed and maximum allowable speed in steps per second, while the slope represents the rate of increase or decrease in velocity per step.

Table 4. Reverberation chamber initialization settings.

Setting	X-axis	Y-axis	Z-axis
Motor step setting	H	H	H
Beginning velocity (sps)	B600	B600	B50
End velocity (sps)	E1400	E1400	E380
Slope	S2	S2	S5
Power setting	P2	P2	P2
Motor direction	N+1	N+1	N+1

Table 4 illustrates all the necessary initialization settings required to ensure appropriate motor movements according to RCs specific needs. As a part of the initialization process, the stirrers and turntable are directed to return to their home position to ensure consistency in starting conditions for each measurement cycle.

### 4.3.2 Motor Control

Once the initialization is completed, both stirrers and the turntable are ready to receive movement commands. Within the control program, mode stirring has been implemented by utilizing the continuous stirred mode. Table 5 presents the movement commands and ranges of the motors.

Table 5. Commands for motor movement.

Motor	Command	Position range (steps)
X-axis	M0, M12000	0 - 12000
Y-axis	M0, M11050	0 - 11050
Z-axis	M0, M4500	0 - 4500

Since initialization returns the stirrers and the turntable to home position, the first command when continuously stirring the chamber is to move all the motors to the end position of their individual range. After the first movement command, program keeps querying the motion controller if motors are ready to take a new command or still in motion. Upon receiving confirmation from the motion controller that motor is ready for another command (>), the program reads the flag variable and instructs the motor to move towards the desired position.

Flag variables for each motor has been included to indicate and determine the direction for the motors. The state of these Boolean values toggles between *True* and *False* after a motor is commanded to move to a specific position, so the program can keep track of which position should the motor be directed to move next.

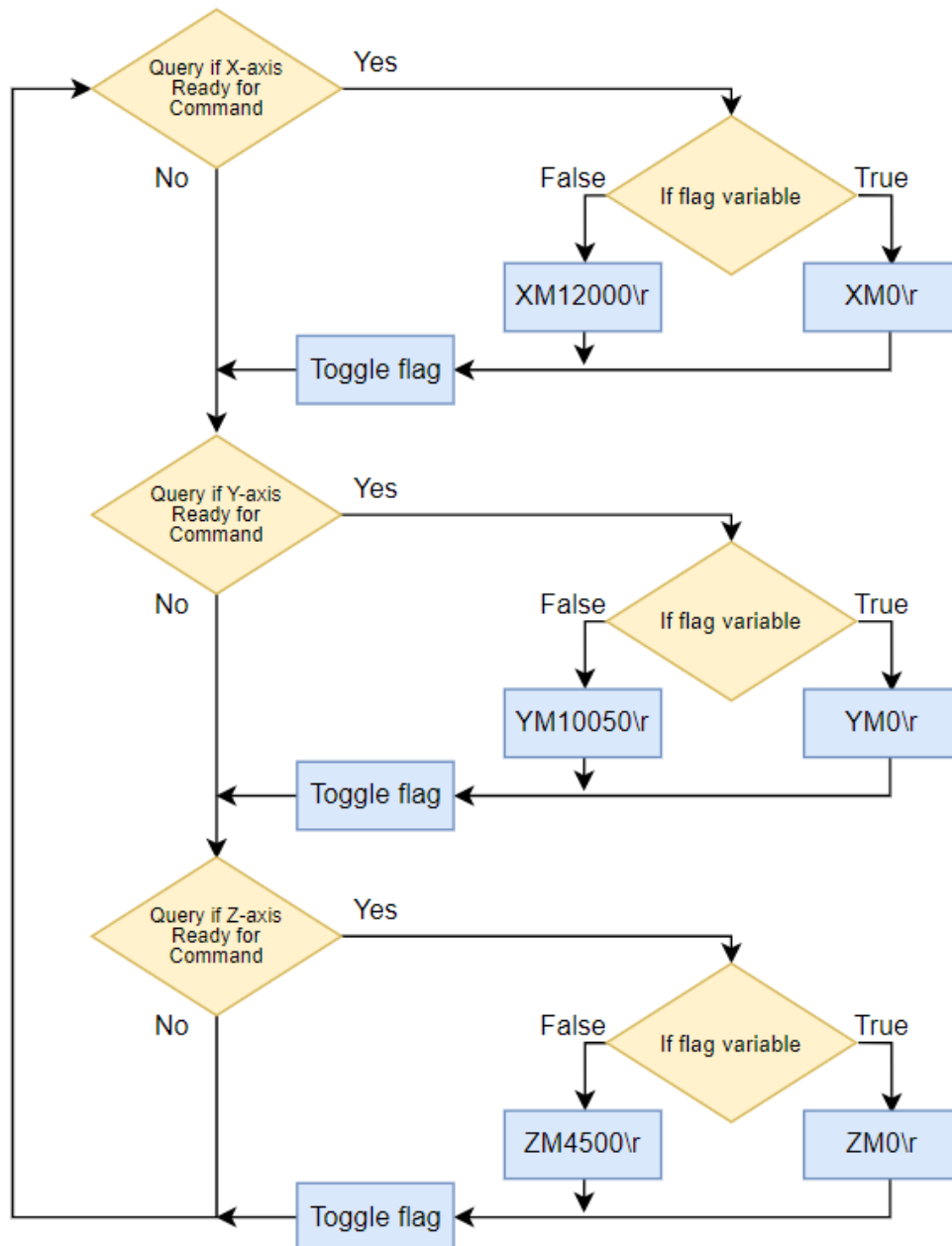


Figure 10. Flowchart of continuous stirring loop.

In figure 10 is demonstrated how the stirrers and the turntable maintain continuous movement by querying the motion controller about the status of the motors, and issuing commands based on their responses and flag state.

### 4.3.3 Integration of Power Monitoring

To include the power meter to the control program, VISA is a necessary component for the control PC to be able to recognize the power meter. The pyVISA Python package is used for the VISA support, facilitating the communication between the power meter and control PC via Python. NRQ6 frequency selective power sensor, manufactured by Rohde & Schwarz, is utilized in the test system.

Table 6. SCPI commands for NRQ6.

SCPI Command	Description
*RST	Sets the instrument settings to default.
FREQuency 2.4E+9	Sets the carrier frequency of the applied signal to 2.4 GHz.
BANDwidth:RESolution 3E+6	Sets the resolution bandwidth to 3 MHz.
BUFFer:STATe ON	Enables the result buffer in continuous mode.
BUFFer:SIZE 131072	Sets the size of the result buffer.
UNIT:POWer W	Sets the format of the measured power values to watts.
INITiate:CONTinuous ON	Starts the continuous measurement.
INITiate:CONTinuous OFF	Ends the continuous measurement.
BUFFer:DATA?	Fetches the measured results from the buffer.
APERture 0.1	Sets the duration of the sampling window to 100 ms.

The control of the power meter via Python is accomplished through SCPI commands, and power measuring has been designed in a way that it operates in sync with the RC. Table 6 contains details of the specific set of SCPI commands that are used in the test system control program.

NRQ6 continuously samples RF power at intervals of 100 ms, and collects all the results into a buffer. Buffer serves as a temporary memory storage, which holds the sampled data and provides efficient data acquisition for later usage.

#### 4.3.4 Test Script

The foundation of the test system control program is built upon the combination of continuous stirring of the RC, while simultaneously measuring the RF power. Figure 11 illustrates a simplified version of the test script workflow.

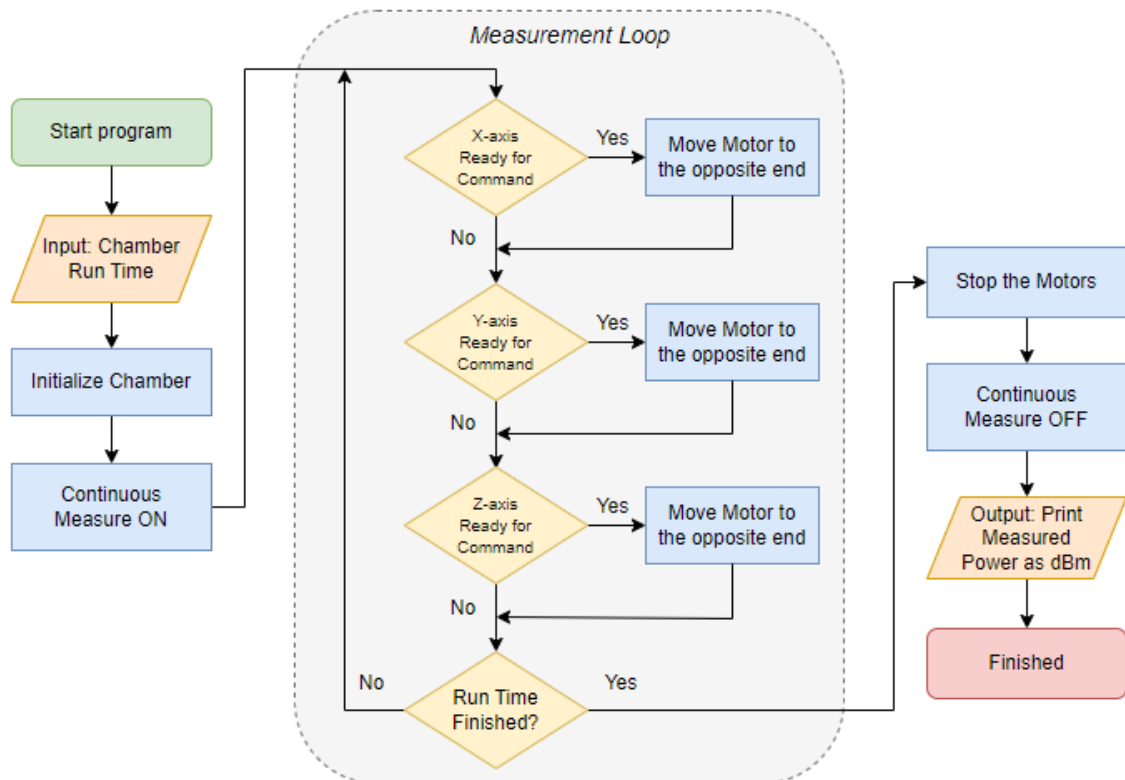


Figure 11. Flowchart of the test script.

Upon initiation of the program, the serial port that the computer has assigned for the RC must be provided. If the default run time of 60 seconds is not desired, the user has an option to specify the run time as an argument in the program. This input defines the measurement duration.

Chamber initialization is performed to make sure that all the motors have been set to the correct settings for the continuous stirring and returned to their home position. The power meter is set to accumulate the measured results into a

buffer and commanded to initiate continuous measurement. Once continuous measuring has been initiated, the RC is commanded to start the stirring.

The measurement loop within the test script iterates until the program detects that previously assigned chamber run time has finished. Once the run time has ceased, all the motors are commanded to stop the movement, and continuous measuring of the power meter is turned off.

The program fetches samples from the power meter's buffer and calculates the average RF power of the results while in watts. After averaging, the result is converted to a dBm (decibel milliwatts) value and printed to the command prompt window, indicating that the measurement has been completed.

The test system control program is a CLI (command line interface) program, meaning that the Python test script is called in command prompt with specific arguments.

```
C:\Reverberation chamber test system>python RC_control.py --help
usage: RC_control.py [-h] [-i] [-r] [-m] [-t] [-s] [-cl]

options:
  -h, --help            show this help message and exit
  -i, --init            Initialize the chamber
  -r, --run             Run the chamber
  -m, --meas           Run the chamber while measuring the power
  -t, --time            Set the running time in seconds, runs for 60 seconds by default
  -s, --serial_port    Define COM port
```

Figure 12. List of the arguments with descriptions.

As illustrated in figure 12, the control program offers options such as independent initialization for returning the stirrers and turntable back to home position. However, if either run or power measure arguments are given, the initialization is not necessary, as these actions already include it as the first step. Figure 13 illustrates the simplicity of measuring the average dBm with the program.

```
C:\Reverberation chamber test system>python RC_control.py --serial_port COM5 --time 120 --meas
Initializing
Runs for 120 seconds
-16.609234786621244 dBm
Finished
```

Figure 13. Example of a RF power measurement.

In the example, Python is used to call the test script (RC\_control.py) with given arguments. The serial port is defined to use COM5, and the control program is instructed to initiate a power measurement for 120 seconds.

Once the script is executed, program will print 'Initializing' to indicate that the initialization is currently in process. After initialization has completed, specified run time is displayed, and the test system proceeds to measure RF power for the desired duration.

Once the measurement has completed, the program outputs the averaged RF power in dBm, and prints "Finished".

## 5 Antenna Efficiency and Total Radiated Power Measurements

This chapter contains an overview of the measurement setup and the methodology used for performing the reference, antenna efficiency (AE) and total radiated power (TRP) measurements.

### 5.1 The Setup

The measurement setup for reference and AE measurements includes a power meter, signal generator, RS-232/USB converter, control PC, and reverberation chamber. The measurement devices used in the test system are manufactured by Rohde & Schwarz. The RC contains a front panel, which works as an interface to access chamber communication and the antennas inside. Port 1 on

the front panel is connected to the turntable, where the reference antenna and/or DUT are mounted, while port A is connected to the fixed measurement antenna. Figure 14 presents the look of the setup and its connections.

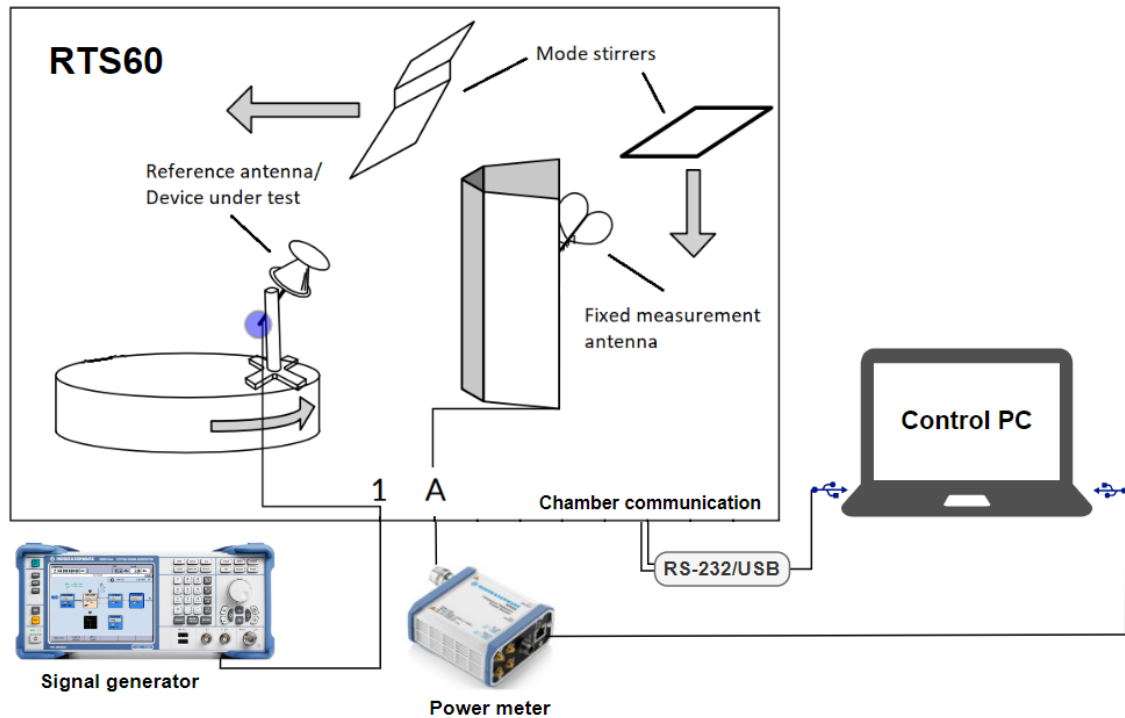


Figure 14. Reference/AE measurement setup.

As the figure 14 illustrates, the signal generator is connected to the reference antenna/DUT through port 1, and the power meter is connected to the fixed measurement antenna via port A. Control of the RC and the power meter are carried out using the control PC, while the signal generator is operated separately. The signal generator was chosen not to be included to the Python test script, as its role in the setup involves a simple job of exciting the chamber with a RF signal at fixed power level and frequency.

## 5.2 Reference Measurement

Reference measurement, where the chamber path loss is determined is essential, and must be performed as a first step. Chamber path loss refers to the EM power attenuation of the radio wave, that occurs when the wave travels

from the reference antenna to the power meter through the chamber, fixed measurement antenna and coaxial cable.

The RF power level of the signal generator is adjusted so that despite all the losses from the cables and antenna, the radiated power of the reference antenna is 0 dBm. After that, the power measurement is conducted with the test program to get the reference power  $P_{ref}$  (dBm). Since the reference antenna is set to transmit 0 dBm, the reference power obtained as a result is equivalent to the chamber path loss value  $P_{PL}$  (dB). Figuring out the reference power and chamber path loss provides a reliable reference point for further testing with the test system.

The setup includes a discone antenna as the reference antenna, with known efficiency of -0.119 dB (97.3%) at a frequency of 2.4 GHz. Performance data for the reference antenna has been provided by Bluetest.

### 5.3 Antenna Efficiency Measurement

Antenna efficiency is a measure of how efficiently EM energy is radiated through the antenna when RF power is fed to the antenna terminal. In case of an ideal antenna, losses would not occur, therefore efficiency would be 0 dB (100%). However, that is not the case in the real world and there are always some losses, caused by impedance mismatches and antenna conduction losses due to conductor generating unintended heat. Antenna efficiency is an essential parameter in assessing the performance of antennas. [13.]

The reference power acquired from the reference measurement is necessary to measure the radiation efficiency of the DUT with the test program.

After the reference measurement has completed and reference power figured out, AE of the DUT can be measured. The reference antenna is replaced with the DUT, and the RF power level of the signal generator is adjusted downward by the amount of efficiency of the reference antenna (-0.119 dB). The AE measurement is then conducted in same exact way as the reference

measurement. Both measurements are required to be executed with the same signal frequency to get reliable results.

Prior to calculating the AE, both the reference power and the measured RF power of the DUT are converted to milliwatts (mW). Equation (1) presents the formula for conversion between dBm and mW.

$$dBm = 10 * \log_{10}(mW) \qquad mW = 10^{\frac{dBm}{10}} \qquad (1)$$

After conversion, the ratio of the measured RF power of the DUT and the reference power is calculated and expressed in dB, which represents the radiation efficiency of the DUT.

$$\text{Antenna efficiency (dB)} = 10 * \log_{10}\left(\frac{P_{DUT}(mW)}{P_{ref}(mW)}\right) \qquad (2)$$

Above is the equation for calculating the efficiency of the DUT, where  $P_{ref}$  represents the reference power, and  $P_{DUT}$  represents the measured RF power of the DUT.

#### 5.4 Total Radiated Power Measurement

Total radiated power (TRP) is a measure of the amount of RF power that is radiated by an antenna when the antenna is connected to an actual radio transmitter. In an ideal scenario with an antenna, TRP would be equal to the conducted input power. However, when using a real antenna, TRP will be weaker than the conducted input power due to factors such as antenna efficiency. [14.] It is an essential measurement for evaluating transmitting performance of the device and its EM energy radiation into the surrounding environment.

The methodology of TRP measurement in RC is almost identical to the reference and AE measurements, except some minor modifications. In the TRP measurement, the signal generator is removed from the setup and antenna on

the turntable is replaced with the DUT. Since the interest is TRP of the DUT, unused connectors in the front panel are plugged and cables removed to prevent any unwanted interference from external signals leaking into the chamber.

The DUT is configured to start transmitting the signal and placed to the holder on the turntable within the chamber. The reference measurement must be done beforehand using the same signal frequency intended for measuring the TRP of the DUT. The test program is then executed to measure the RF power. TRP of the DUT is obtained by adding the chamber path loss to the measured power.

$$\text{Total Radiated Power (dBm)} = P_{DUT} \text{ (dBm)} + P_{PL} \text{ (dB)} \quad (3)$$

In equation (3),  $P_{DUT}$  represents the measured RF power value of the DUT, while  $P_{PL}$  refers to the chamber path loss.

## 6 Measurement Results and Analysis

In this chapter, the measurement results will be analyzed. The measurements were executed as described in the previous chapter.

### 6.1 Chamber Path Loss and Stabilization

The chamber stabilization time refers to the duration after which the average RF power of the results can be considered reliable.

The reference measurement, which is illustrated in figures 15, 16 and 17 was conducted with frequency of 2.4 GHz to obtain correct chamber path loss value for further measurements.

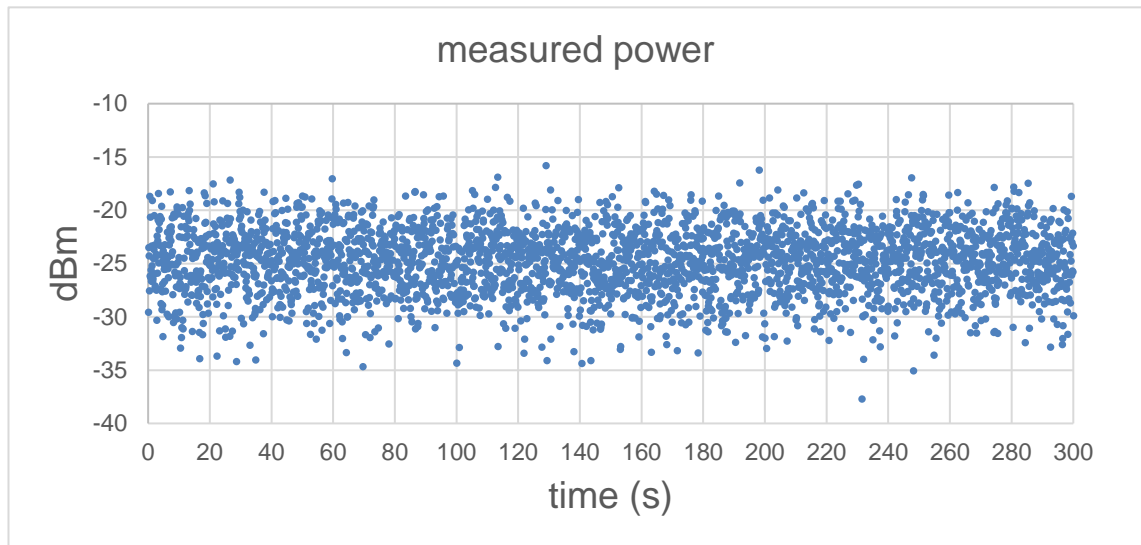


Figure 15. Measured RF power with sampling time of 100 ms.

The power meter is configured to measure with a sampling time of 100 ms, initiating a new measurement as soon as the previous one ends. All sampled values throughout the reference measurement fell within the range of -40 dBm and -15 dBm.

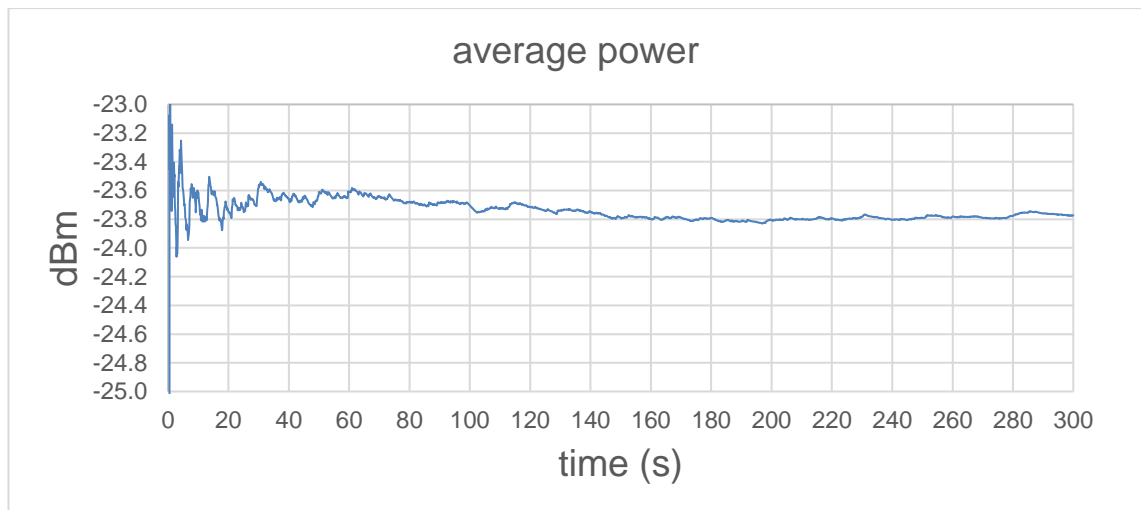


Figure 16. Averaged RF power over time.

Examining figure 16 shows that when averaging the samples over time, it takes only approximately 20 seconds to obtain a relatively consistent averaged value

without a lot of fluctuations. By around 150 seconds, the averaged result has fully stabilized at -23.8 dBm, representing the chamber path loss at the specific frequency used.

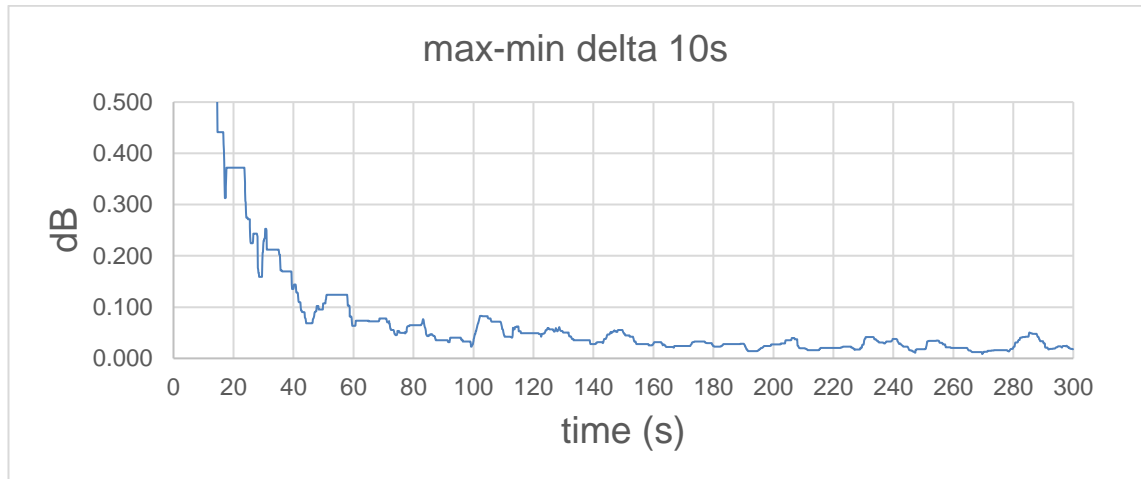


Figure 17. Delta of maximum and minimum values.

By analyzing the difference between the maximum and minimum values of the averaged measurement results over a 10-second interval, additional information about averaged value fluctuations is gained. Figure 17 indicates that after 60 seconds of stirring and measuring the chamber, the difference between the maximum and minimum averaged RF power over the last 10 seconds remains within 0.1 dB. This difference can serve as an indicator to determine when the chamber has stabilized.

## 6.2 Antenna Efficiency

For AE measurement, the antenna used as a DUT is Cisco Aironet Dual-band Dipole Antenna, which is mounted on the turntable in the place of the reference antenna, as shown in figure 18.

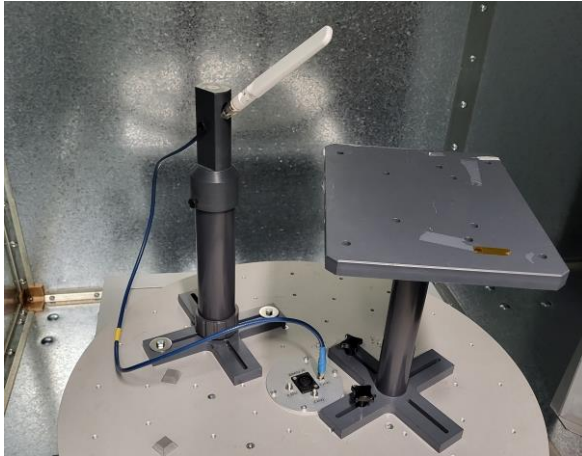


Figure 18. Cisco dipole antenna as a DUT.

As was shown before, it took approximately 150 seconds to get fully stabilized results in the chamber measurements, therefore the DUT was measured for the same duration. Measured RF power was -24.7 dBm, and the reference power was earlier found to be -23.8 dBm at 2.4 GHz. By applying equation (1) to convert dBm values to mW, followed by equation (2), the AE of the DUT can be calculated.

$$\text{Antenna efficiency} = -0.9 \text{ dB (81.3\%)}$$

Cisco does not provide the radiation efficiency information of their antennas, so it cannot be confirmed that the measured efficiency is correct.

### 6.3 Total Radiated Power

The Portrait Mobile was selected as a DUT for the TRP measurements due to its prior characterization. TRP of the device has been previously measured by Verkotan, which is a company specializing in accurate wireless device testing services. By taking advantage of the known TRP of the Portrait Mobile, the reliability of the measurement results obtained with the test system can be confirmed. Figure 19 illustrates how the Portrait Mobile was mounted in the turntable.

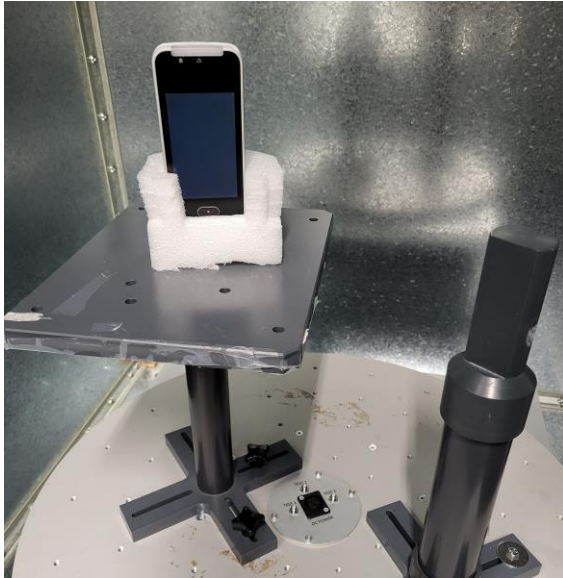


Figure 19. Portrait Mobile as a DUT.

Measurements were conducted with four different DUT configurations, each having a known TRP. Equation (3) was applied to compute the outcomes of the test system measurements to obtain the TRP.

Table 7. Measurement result comparison.

	Measured at Verkotan (dBm)	Measured with RC (dBm)
<b>Case 1</b>	9.4	9.7
<b>Case 2</b>	9.1	9.2
<b>Case 3</b>	0.6	0.5
<b>Case 4</b>	0.4	0.2

By examining the table 7, it is evident that the results obtained with the reverberation chamber test system closely align with the results measured by Verkotan.

## 7 Conclusion

The thesis provides a simplified explanation of reverberation chambers, avoiding complex mathematics and theory to ensure clarity for the reader. The intention was to present the operational principles of a RC in an understandable manner.

Main goals of this thesis work were to implement the RTS60 Reverberation Test System and develop a test system control program for operating and conducting OTA measurements with the RC. Both goals were achieved through steps that were thoroughly explained in previous chapters.

Reverse engineering of the RTS60 provided insight into the chamber's operational mechanism, and the information acquired from the process was used as a foundation for developing the control program. The programming was carried out using Python and structured in a modular architecture.

The reference measurement was conducted with the test system control program to obtain the chamber path loss value, which served as a reference point for following measurements. Results also provided explanation in practice how the measured RF power is averaged over time and stabilization of the chamber achieved.

The TRP of the Portrait Mobile was measured using four different configurations of the device, and the results were compared to the TRP provided by Verkotan. In all four configuration cases measured by RTS60 and Verkotan, the results aligned very closely with each other, with a maximum difference of 0.3 dB.

Since Cisco does not provide the efficiency of the dipole antenna, the accuracy of AE measurement cannot be confirmed. However, considering the accuracy of the TRP measurements, RTS60 seems to measure the transmitted RF power of the DUT quite accurately. Therefore, the measured AE of -0.9 dB (81.3%) may closely approximate the dipole antenna's actual radiation efficiency.

As demonstrated in this thesis, RCs provide an efficient method for conducting OTA measurements on wireless devices. While RCs have limitations such as losing the information about polarization and radiation pattern of EM waves, these features are often less significant in many wireless applications. Instead, properties such as radiation efficiency hold greater importance.

The thesis work has delivered a functional reverberation chamber test system for the company and outcome can be concluded as a success.

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