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Controllable Multiplexer for High Frequency Signals

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Abstract

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Calibration of a multichannel oscilloscope using a single channel source requires a significant amount of manual labour or an automated system. Adding automation will relieve the human resource for other tasks, thus dramatically improving efficiency. Additionally, it reduces the factor of human error which in the end improves reliability and reproducibility of the whole process.

Purpose of this project was the design and realization of an external automation system for the calibration of multichannel oscilloscopes for SGS Fimko Ltd's calibration laboratory. The objective of the thesis work was to implement and test an embedded system which acts as a controllable multiplexer/demultiplexer for high frequency signals, from DC up to at least 2.5 GHz.

The characterizing of the boards was carried out using a vector network analyser and the testing of the communication and logic were tested with an oscilloscope.

The final product was found to be usable for calibration procedures on the previously mentioned range when applying the correction factors to the measurement results. For further studies it is recommended to use more measuring equipment as well as designing a custom RF board.

Keywords: radio frequency, calibration, automation

The originality of this thesis has been checked using Turnitin Originality Check service.

Contents

List of Abbreviations

1	Introduction	1
2	Calibration	1
2.1	Importance of Calibration	1
2.2	Metrological Traceability	2
2.3	Uncertainty in Measurement	3
2.3.1	Evaluation of Standard Uncertainty	3
2.3.2	Combined and Expanded Uncertainty	4
2.3.3	Error	5
3	Theoretical Background	6
3.1	Automation	6
3.1.1	Communication	6
3.1.2	Relation of Devices	7
3.2	RF Signals	8
3.2.1	Impedance	8
3.2.2	Transmission Line	9
3.2.3	Impedance Matching	10
3.2.4	Voltage Standing Wave Ratio (VSWR)	10
4	Methods and Materials	11
4.1	Design Methods	11
4.1.1	RF Circuit Design	11
4.1.2	Using a Ready-made Board	11
4.2	Materials	12
4.2.1	Board 1	12
4.2.2	Board 2	13
4.3	Programming	13
4.4	Testing	15
4.4.1	Code Testing	15
4.4.2	RF Switch Board Testing	16
5	Results	17

5.1	Measurement Results for Board 1	17
5.2	Measurement Results for Modified Board 1	19
5.3	Measurement Results for Board 2	21
5.4	Uncertainties	23
6	Discussion	25
7	Conclusions	25
	References	27

List of Abbreviations

AC:	Alternating Current
BIPM:	Bureau International des Poids et Mesures
CPU:	Central processing unit
DC:	Direct Current
DMM:	Digital Multimeter
DUT:	Device Under Test
FINAS:	Finnish Accreditation Service
GPIO:	General Purpose Interface Bus
HF:	High Frequency
IDE:	Integrated Development Environment
ILAC:	International Laboratory Accreditation Cooperation
ISA:	International Society of Automation
ITU:	International Telecommunication Union
JCGM:	Joint Committee for Guides in Metrology
MCU:	Microcontroller Unit
PCB:	Printed circuit board
RF:	Radio frequency

SI:	The international system of units.
UART:	Universal Asynchronous Receiver-Transmitter
USB:	Universal Serial Bus
VNA:	Vector Network Analyzer
VSWR:	Voltage Standing Wave Ratio
VTT MIKES:	Finnish National Metrology Institute

1 Introduction

The thesis work was done for SGS Fimko Ltd. SGS is a Swiss multinational company providing services in the field of inspection, verification and testing. The Finnish branch is the combination of two companies SGS Finland Ltd. and SGS Fimko Ltd [11]. The company's calibration laboratory is located in Helsinki and provides a wide range of calibration services. The goal of the project was to further improve the laboratory's automation process in the area of oscilloscope calibration using a remotely controllable multiplexer.

The calibration of a multichannel oscilloscope, whether it is 4, 6 or 8 channels can take hours if the whole process is done manually. With an automated system, not only the time it takes to finish the job is reduced, but it frees up labour as well, improving the efficiency of the laboratory without additional workload. Using a single channel source such as a Fluke 552xA means the constant switching of channels and settings of both the oscilloscope and the multipurpose calibrator. This can lead to a bottleneck in the workflow of a smaller laboratory, and it leaves the possibility of human error in the process.

2 Calibration

Calibration is the process of comparing the DUT to a more precise measure while providing metrological traceability.

2.1 Importance of Calibration

Calibration indicates to the customer, owner and user, the condition of the device or measurement system. With this information these can be adjusted or corrected by a correction factor, hence providing more reliable and accurate measurement results, which can be traced back to the corresponding SI units [1].

Laboratories must conform to several standards and guidelines for the calibration to be reliable and internationally accepted, such as ISO/IEC 17025 (General requirements for the competence of testing and calibration).

2.2 Metrological Traceability

For a device to be metrologically traceable it requires an unbroken chain of calibration from a specific unit of the SI. The SI units are defined in terms of constants that describe the natural world and are maintained by the BIPM [2]. Accreditation bodies covered by the ILAC Arrangement provide accreditation to laboratories. In Figure 1 below shows a traceability triangle which explains how traceability is transferred from NMIs to the customers.

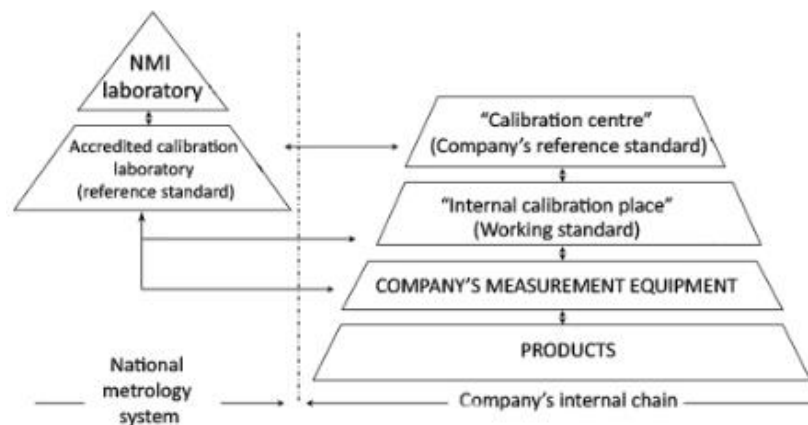


Figure 1. Traceability triangle [1]

In Finland the NMI is VTT MIKES and the traceability of measurement standards is transferred to accredited calibration laboratories such as SGS Fimko Ltd.'s calibration laboratory. All of these steps increase the uncertainty of calibration, thus the closer a calibration is to the NMIs and the base SI units, the smaller the uncertainty. These calibrations form a chain of comparisons. To achieve the realisation of metrological traceability it is necessary to have an unbroken chain of comparisons, which can be traced back to the SI units. The requirements listed by FINAS are [1.]:

- All parts of the chain have a calibration certificate,
- Measurement uncertainty is known and notified,

- Calibrations are performed in a competent manner,
- Measurement methods and results have been documented,
- Equipment can be identified,
- Re-calibrations are performed at specific intervals.

2.3 Uncertainty in Measurement

Measurement uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. Uncertainty reflects the lack of exact knowledge of the value of the measurand. [7, 2.]

There are several possible sources of uncertainty but the most common and effectful are [7, 6.]:

- imperfect realization of the definition of the measurand,
- nonrepresentative sampling,
- environmental conditions or rather the lack of knowledge of these conditions,
- personal bias in reading analogue instruments,
- resolution,
- inexact values of measurement standards, constants and other parameters,
- variations in repeated observations under apparently identical conditions.

2.3.1 Evaluation of Standard Uncertainty

There are two types of evaluations when it comes to uncertainty, Type A and Type B.

Type A evaluation of uncertainty is obtained from repeated measurement results under the same conditions. This evaluation method is used when the result varies randomly. The measurement result is taken as the arithmetic mean of n measurements and the standard uncertainty is the estimated standard deviation on the mean. Thus, the distribution of values can be best described as a normal distribution. In Figure 2 below μ_t represents the arithmetic mean and σ represents the standard uncertainty.

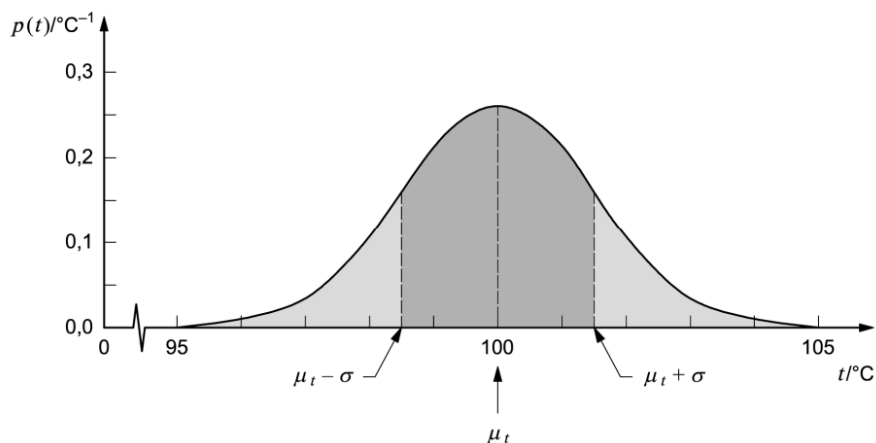


Figure 2. Normal distribution diagram [7, 16]

Type B uncertainty is most often used when the only available knowledge of a value is that it lies in an interval. Such cases can be best described with rectangular or triangular distribution. Figure 3 below shows that the value lies between limits a^- and a^+ , where μ_t represents the value and $a/\sqrt{3}$ represents the standard uncertainty.

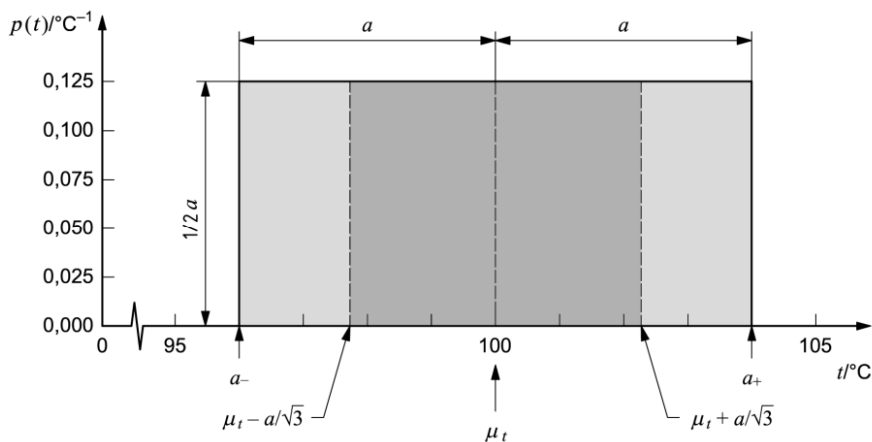


Figure 3. Rectangular distribution [7, 17]

2.3.2 Combined and Expanded Uncertainty

Combined uncertainty is the combination of all standard uncertainties of the measurement. It is calculated as the square root of the sum of standard uncertainties squared:

$$\mu_c = \sqrt{\mu_{t1}^2 + \mu_{t2}^2} \quad (1)$$

Expanded uncertainty is the interval which includes a large fraction of values of the distribution. This fraction is often referred to as level of confidence.

Coverage factor is a multiplier of the combined uncertainty to obtain the desired level of confidence. It is most often 1, 2 or 3, with a coverage factor of 1, the level of confidence is 68%, with 2 it's 95% and with 3 it is 99.7%. In calibration the level of confidence most often used is 95%, which means a coverage factor k of 2.

$$\mu = \mu_c \cdot k \quad (2)$$

2.3.3 Error

While there is a relation between the concepts of error and uncertainty, uncertainty and error are not to be confused with each other. Error is the difference between a measurement and the true value being measured [8] while uncertainty reflects the lack of exact knowledge of the value of the measurand [7, 5.]. Traditionally there are two types of error, systematic and random. Figure 4 shows a visualisation of the difference between random and systematic error.

Systematic error means a quantifiable, systematic shift in all measurements. Systematic errors can be reduced by applying a correction factor to the results.

Random error is unknown and unpredictable, nonetheless it can be reduced by increasing the number of observations.

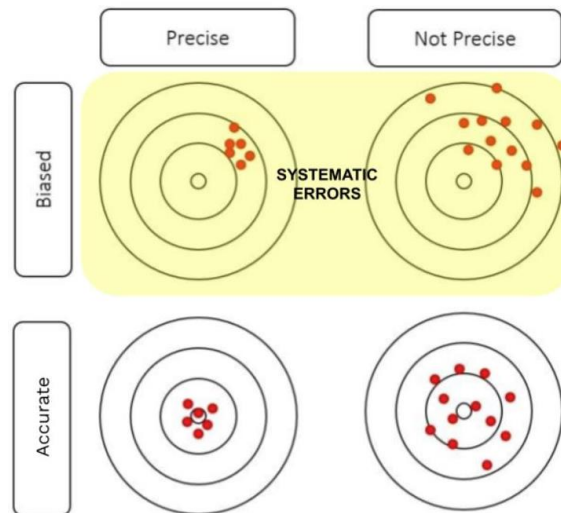


Figure 4. Systematic and random error

3 Theoretical Background

Since the project aimed at creating an automated system which works with RF signals, some concepts need to be defined before proceeding to describe how the system works and why.

3.1 Automation

Automation is the use of technology where tasks are performed in to minimize or eliminate human intervention from the system. Due to automation being a broad topic as it is used in several applications from transportation, agriculture, manufacturing to robotics, the main aspect of automation in this thesis is how devices in the system communicate with each other and in what relation these devices are to each other.

3.1.1 Communication

An automation system consists of several devices which communicate with each other, receive, send, process instructions and perform tasks based on them. Communication must be reliable and predictable for a system to be efficient, thus the speed, size and structure of these messages have a large impact. The size of these messages needs to be as small as possible, while containing all the required information; the structure needs to be straightforward, for easier decoding. However, each command needs to be

clearly separated and recognizable to avoid misread instructions. The speed of communication depends on the size of the messages and the communication protocol. The communication protocols used in this project are USB and GPIB.

GPIB, also known as IEEE-488.2 or HP-IB (Hewlett-Packard Interface Bus), was first established by the Hewlett-Packard Company to allow parallel data transfer between its large range of automated test equipment and is one of the most widely recognized and used method for communication between instruments to this day.

USB is as its name states a universally usable industry standard for serial communication developed by several companies, in order to standardize peripheral connections. It was first released in 1996 and it has been improving ever since then.

3.1.2 Relation of Devices

Network topology describes how devices in a system are connected and related to each other in a network [5]. There are various types with all of them having their own advantages, disadvantages and different use cases. A few examples of such topologies are shown in Figures 5, 6 and 7:

- ring topology,
- star topology,
- and line topology.

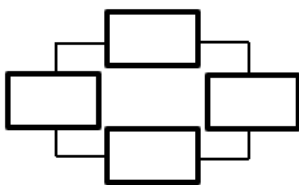


Figure 5. Ring topology

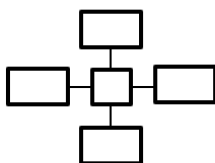


Figure 6. Star topology

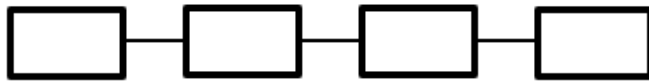


Figure 7. Line topology

During this project, the used network topology is a combination of ring and star topology, since the computer is going to be the middle point to which everything is connected, including the microcontroller. Due to using GPIB protocol, all devices, excluding the microcontroller, are connected to each other.

3.2 RF Signals

RF signals are AC signals which lie on the radio spectrum. The bandwidth of the radio spectrum is defined several ways but the most general is 3 kHz to 300 GHz, which can be cut into several bands.

The bands are listed as such by ITU [3.]:

- Very low frequency (VLF) 3 – 30 kHz,
- Low frequency (LF) 30 – 300 kHz,
- Medium frequency (MF) 300 – 3000 kHz,
- High frequency (HF) 3 – 30 MHz,
- Very high frequency (VHF) 30 – 300 MHz,
- Ultra-high frequency (UHF) 300 – 3000 MHz,
- Super high frequency (SHF) 3 – 30 GHz,
- Extremely high frequency (EHF) 30 – 300 GHz.

3.2.1 Impedance

Impedance is the property of an AC circuits describing its total opposition to electric current [9]. The difference between resistance and impedance is that impedance has magnitude and phase while resistance only has magnitude. Impedance is a combination of the resistance and reactance. It is often represented as a complex number, which is how it is going to be represented in this thesis as well. The real part represents resistance, while the imaginary part represents reactance,

$$Z = R + jX. \quad (3)$$

The impedance of an ideal resistor is purely real, since an ideal resistor is independent from frequencies, thus it can be mathematically written as:

$$Z_R = R + j0. \quad (4)$$

A capacitor's impedance is dependent on the frequency of the signal, and it is calculated as:

$$Z_C = \frac{1}{j\omega C}. \quad (5)$$

The Greek letter omega, ω , is used to represent the angular frequency which can be calculated by using Equation (6) in which f represents the frequency in Hz,

$$\omega = 2\pi f. \quad (6)$$

3.2.2 Transmission Line

A transmission line is the medium that forms a path from one place to another directing the transmission of energy in the form of electromagnetic, acoustic waves or electric power [4, 7].

A transmitted signal will experience reflection between the load and the transmission line. This is a generally unwanted behaviour to achieve efficient power transfer, thus the load impedance and the characteristic impedance of the transmission line need to be matched [4, 221.].

The characteristic impedance of a transmission line represents the resistance of a transmission line in the case of it being infinitely long and it can be calculated using equation (7), in which L and C are the inductance and capacitance per unit length of line [10].

$$Z_0 = \sqrt{\frac{L}{C}} \quad (7)$$

The most common characteristic impedance is 50 ohms but often 75 ohms is used as well depending on the application.

In the case of this project the transmission line is the whole device since it is put between the source and the DUT, thus it is beneficial to take the impedances into consideration as well and possibly perform changes to match the impedances. The characteristic impedance of the device is 50 ohms.

3.2.3 Impedance Matching

Impedance matching is fundamental in RF circuits, since mismatched impedance creates undesired reflections, thus the signal at the receiving end is corrupted compared to the source. To achieve this goal, an ideal case is that the impedance of the source, the line and the load are all the exact same.

3.2.4 Voltage Standing Wave Ratio (VSWR)

VSWR is a characteristic of RF circuits. It shows how much of the power is being reflected. It can be calculated from the reflection coefficient, which is represented by the Greek letter gamma, Γ . The reflection coefficient depends on how well the impedance of the circuit is matched and it can be calculated from the load and characteristic impedance and can be calculated using Equation (8),

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (8)$$

As can be deduced from Equation (8), the closer the load impedance is to the characteristic impedance, the less the reflection coefficient is. In an ideal case the reflection coefficient is 0, in the worst possible case it is close to 1. From this the VSWR can be calculated using Equation (9),

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (9)$$

The closer the VSWR is to 1, the less power is being reflected. In an ideal case the VSWR is exactly 1, meaning that the signal is the exact same at the receiver and the source.

4 Methods and Materials

During the planning of this project two possible implementations came up. Designing an RF circuit switch board or using an already designed and manufactured board.

4.1 Design Methods

Both options have their advantages and disadvantages thus there was need to compare these and decide which one fits the scope of the project better.

4.1.1 RF Circuit Design

There were several points supporting this method such as, designing a fresh board would allow to have a device which provides the exact capabilities the laboratory is looking for, nothing more, nothing less. This method would also allow all components of the circuit to take place on one single PCB and materials wise it would be a cheaper option. On the other hand, there are more pressing points against this method. To design a well-functioning RF circuit board, it requires experience and a deep understanding to RF signal theory. It would take significantly more time while the possibility of having an error in the design is largely increased.

4.1.2 Using a Ready-made Board

This method may not be best option all the time but most often it is the most efficient way forward. This way the workload and the possibility of design flaws are significantly reduced. Manufacturers provide datasheets and measurement results for the customer, which in turn makes it easier to pick a board which better suits the application.

For this project the latter option was pursued, due to designing a new board is deemed unnecessary and this way the focus is on the testing of such a board and implementing it in calibration procedures, instead of designing it.

4.2 Materials

For the RF switch circuit two boards with different bandwidths were chosen, EV1HMC253AQS24 and EV1HMC253ALC4 evaluation boards, both designed and manufactured by Analog Devices. They are compact and provide the exact functionalities required. According to the manufacturer these boards are to be used in the range of 0Hz – 2.5 GHz and 0Hz – 3.5 GHz. However, before use they do need to be altered so that they can be used with BNC cables since originally both boards have 3.5 mm coaxial connectors. Additionally, both boards have capacitors at the input and the output as well, which is not ideal since capacitors block the DC signals and they are to be used with DC signals as well. Later, during testing this needs to be looked at and possibly resolved.

The control unit of the device is a microcontroller board. Due to the simplicity of the logic required, there is no need to have a dive-deep into the world of different high-end microcontrollers and PCB design, thus a simple Arduino board is sufficient. The chosen microcontroller board is an Arduino UNO Rev3, which has a USB Type B connector and external voltage input as well, in case in the future it would be controlled over a wireless network.

4.2.1 Board 1

The first option for the RF switch board was the EV1HMC253AQS24. According to the manufacturer this evaluation board has a bandwidth of DC to 2.5 GHz, which means it is more than capable to be used for this project and additionally it is a great option even when using newer calibrators which are up to 2 GHz. There are two of these boards, in case there is a need to modify one of them. Figure 8 shows the physical board.

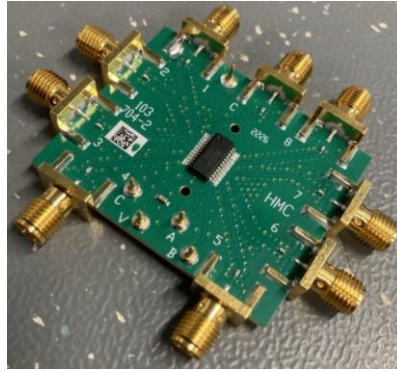


Figure 8. EV1HMC253AQS24 Evaluation board

4.2.2 Board 2

The second board is the EV1HMC253ALC4. This board has a bandwidth of DC to 3.5GHz. Its physical dimensions are approximately the same and its operation is the exact same as the previously mentioned board, with the exception of the control pin locations. Figure 9 shows the physical board.

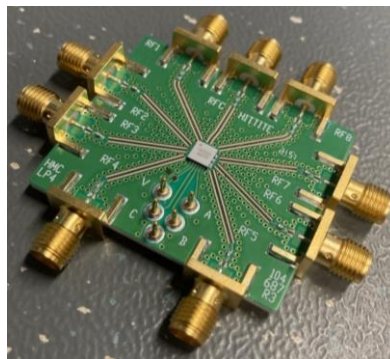


Figure 9. EV1HMC253ALC4 Evaluation board

Since both boards are using different components their RF properties are different as well, thus they need to be tested separately and the results should be compared to determine which one is better suited to achieve the goals of this project.

4.3 Programming

The MCU receives messages from the computer through USB, which then processes it and executes the corresponding task. The code is written in the programming language C using Arduino IDE. There are 2 main commands it can interpret, which are as follows:

- *RST – Reset the system to default settings.

- Channel x – Switch to channel “x”.

Sending *RST can be used to set the board back to its original settings, thus resetting it. Channel x is the command which allows the user to switch between channels by replacing x with the channel number in the command. The channels are controlled by A, B, C pins for which the truth table is:

Control Input			Signal Path State
A	B	C	RFCOM to:
Low	Low	Low	RF1
High	Low	Low	RF2
Low	High	Low	RF3
High	High	Low	RF4
Low	Low	High	RF5
High	Low	High	RF6
Low	High	High	RF7
High	High	High	RF8

Table 1. RF switch truth table [6]

As can be seen from Table 1 above, the inputs represent a binary value meaning that C is the most significant bit and A is the least significant bit. Due to this, the values used to control the output are represented in binary in the code by the variable state.

Each time the function setting the output is called, the bits are checked by bit shifting and the corresponding pins are set HIGH if the bit is 1 and set LOW if the bit is 0. The function can be seen in Listing 1 below.

```
void channel_switch(int new_state){
    if(new_state & (1 << 0)){ //checking least significant bit
        digitalWrite(A, HIGH);
    }else{
        digitalWrite(A, LOW);
    }

    if(new_state & (1 << 1)){ // checking middle bit
        digitalWrite(B, HIGH);
    }else{
        digitalWrite(B, LOW);
    }

    if(new_state & (1 << 2)){//checking most significant bit
        digitalWrite(C, HIGH);
    }else{
        digitalWrite(C, LOW);
    }

    state = new_state;
}
```

Listing 1. channel_switch function

Communication from the computer is through USB with the baud rate of 9600 since timing is not a critical factor in this application.

4.4 Testing

The testing was done first for the MCU which was later used to control and power the evaluation boards during tests.

4.4.1 Code Testing

The testing of the code was done by feeding the commands through the computer using the serial monitor.

Checking if the MCU sets the correct output pins can be checked by connecting another MCU to those pins which reads them. It can also be checked manually by connecting 3

DMMs to those pins and measuring the voltages they output or using a multichannel oscilloscope and connecting each output to a separate channel, this way it is also easier to visualize the change of the outputs, thus this method was chosen. When the pin is set to LOW, the output should be close to 0 V, thus grounded and when set to HIGH it should output close to 5V. The RF boards register an input as HIGH as long as it is above 2 V and as LOW if it is below 0.8 V, so there should be no need to further stabilize the signal. If the control signals are between 0.8 V and 2 V, it may cause unwanted behaviour thus it is recommended to stick with the specifications provided by the manufacturer. Figure 10 below shows the testing setup of the microcontroller.

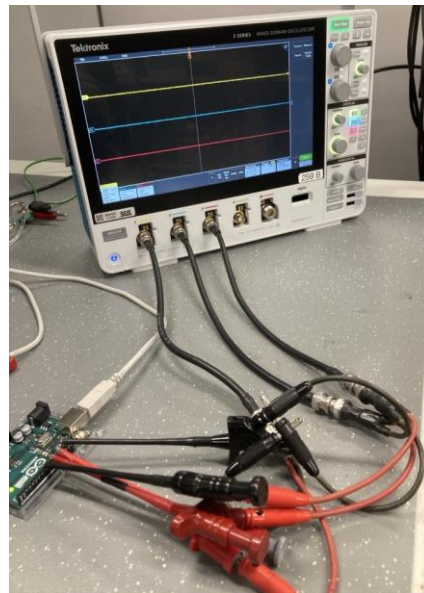


Figure 10. MCU testing setup using a multichannel oscilloscope.

4.4.2 RF Switch Board Testing

The larger part of the testing was to determine how well the RF switch boards work and how they affect the signal on each channel. This was done by running a sweep across their frequency range with a Keysight E5080B ENA Vector Network Analyzer. The results of these tests were crucial to determine the capabilities of the project and the correction factors for later use. All 4 scattering parameters, S_{11} , S_{12} , S_{21} , S_{22} were measured and using these it is possible to determine the gain, loss, VSWR and impedance as well. These parameters describe the behaviour of the board at the measured frequencies. The VNA was calibrated using HP 85052D calibration kit. Figure 11 shows the testing setup of the RF switch boards.

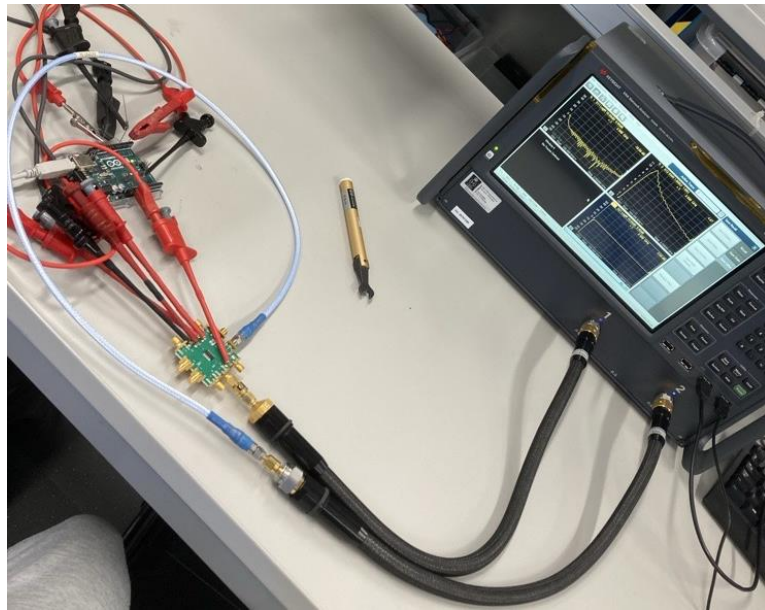


Figure 11. RF Board testing setup with VNA

5 Results

The results of the tests for both boards are from the measurements which were done with the VNA for all channels on both boards. To determine what are the differences and which one functions better, these results need to be compared. Since all channels show fairly similar results on each board, all results stated are for channel 1 of each board. All the measurements with the VNA were done with averaging of 32 sweeps and intermediate frequency of 100 Hz, as well as the sweep type of segment sweep.

5.1 Measurement Results for Board 1

Figure 12 shows the gain for the whole frequency range of the board. It is clearly visible that at lower frequencies the insertion loss is so high that the board is unusable at its current state.

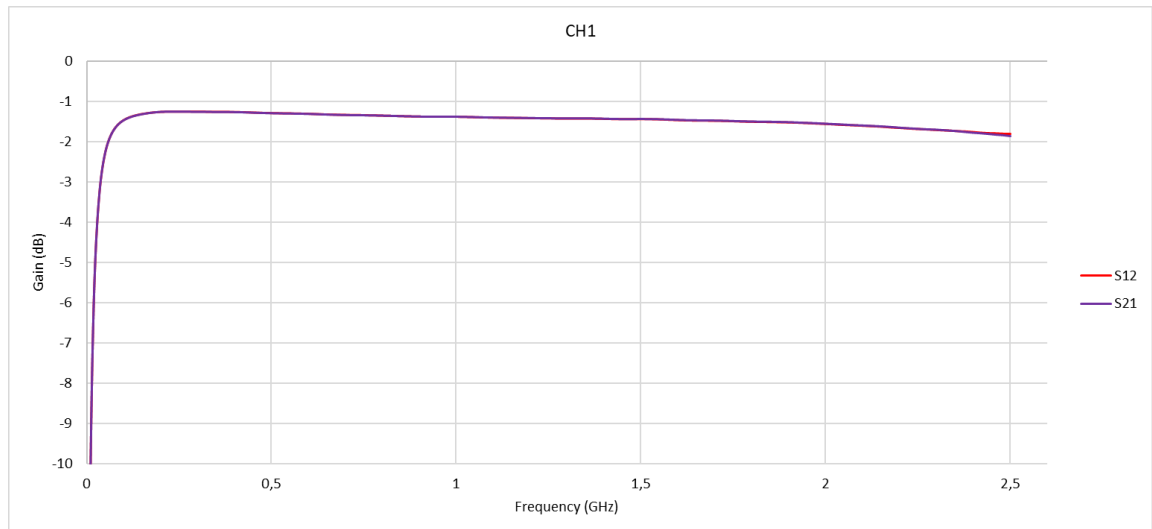


Figure 12. Gain on the full frequency range of Board 1

The results for S21 and S12 are fairly uniform which is expected since they are the same measurements with the only difference being the direction. Up to the tipping point, the gain is extremely little and after taking a closer look at the lower frequencies in Figure 13, it becomes visible, that the gain only enters the ± 3 dB zone around 40 MHz.

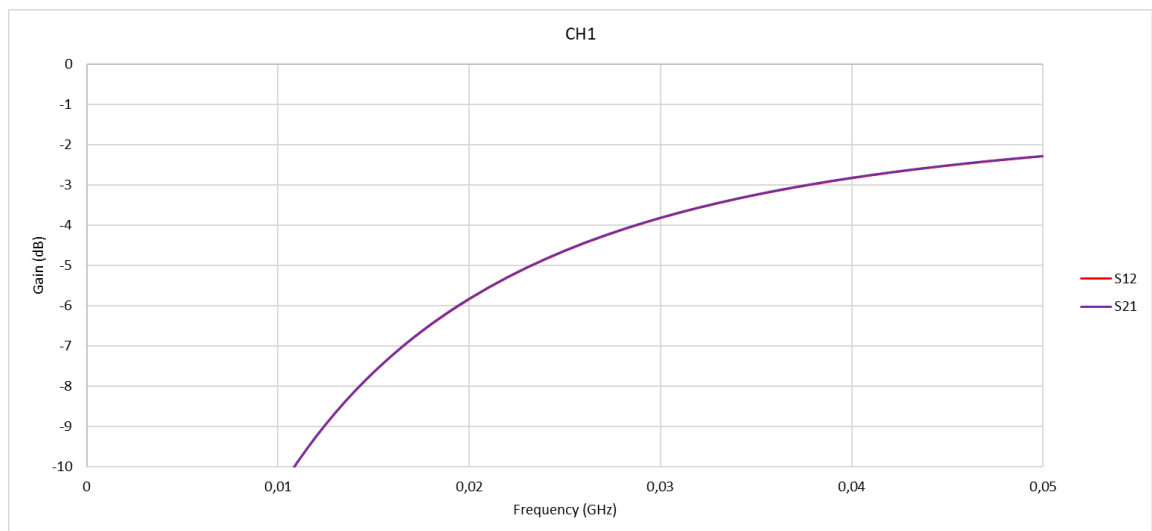


Figure 13. Gain of Board 1 up to 50 MHz

The explanation for this behaviour is that the board has DC block capacitors at both the input and the output resulting in high impedance at lower frequencies, since capacitors are frequency dependent and the higher the frequency, the lower the impedance is in return. This in turn results in large VSWR, which is shown in Figure 14.

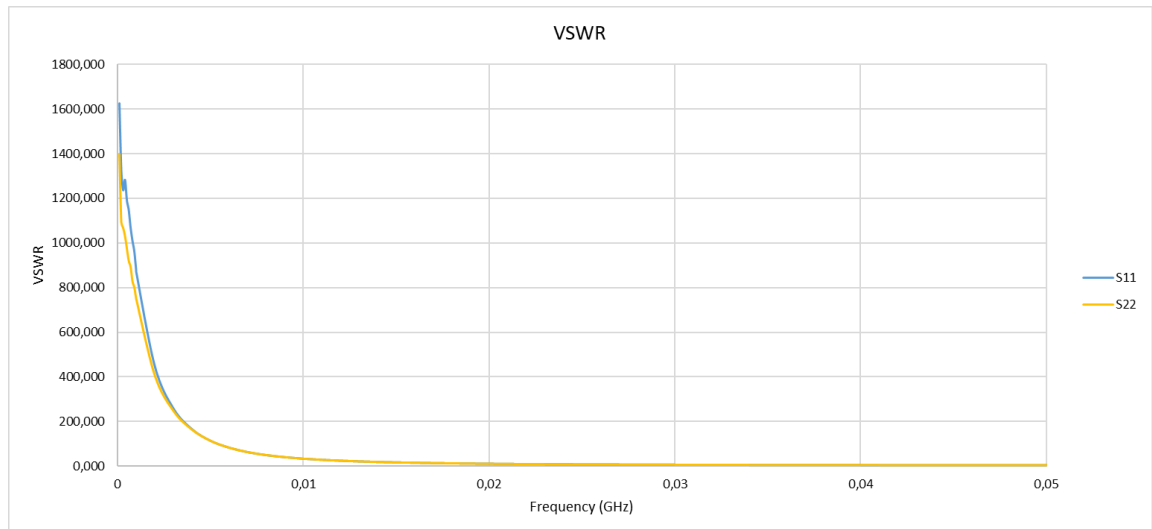


Figure 14. VSWR of Board 1 up to 50 MHz

As can be seen in Figure 15, at higher frequencies the VSWR is normal and closer to 1 which is expected considering the problem with the gain is apparent only at lower frequencies.

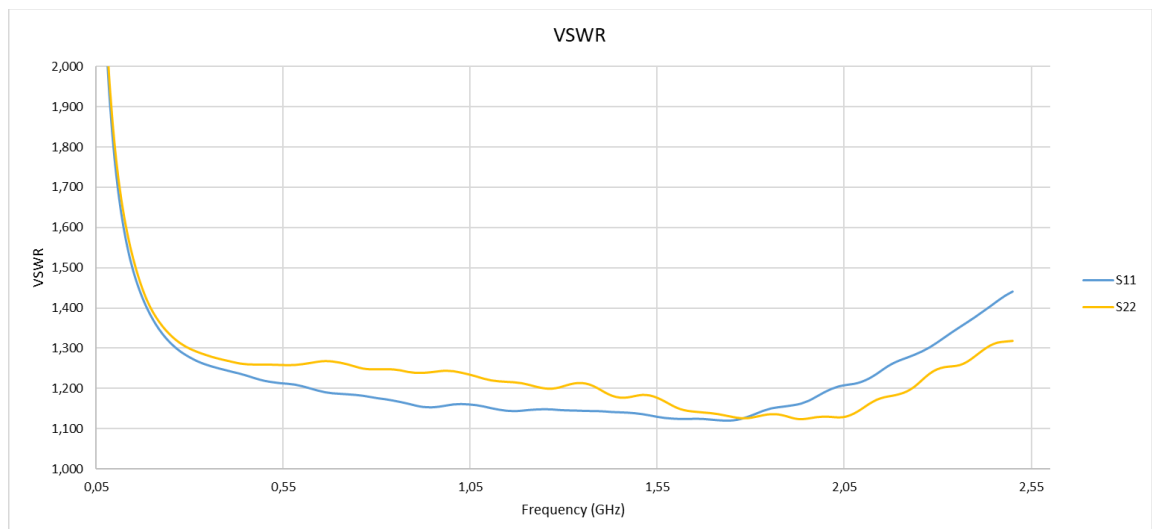


Figure 15. VSWR of Board 1 from 50 MHz

5.2 Measurement Results for Modified Board 1

In order to correct this issue, the capacitors have been removed from the board and all the measurements were done another time. The gain after removing the capacitors is shown in Figure 16.

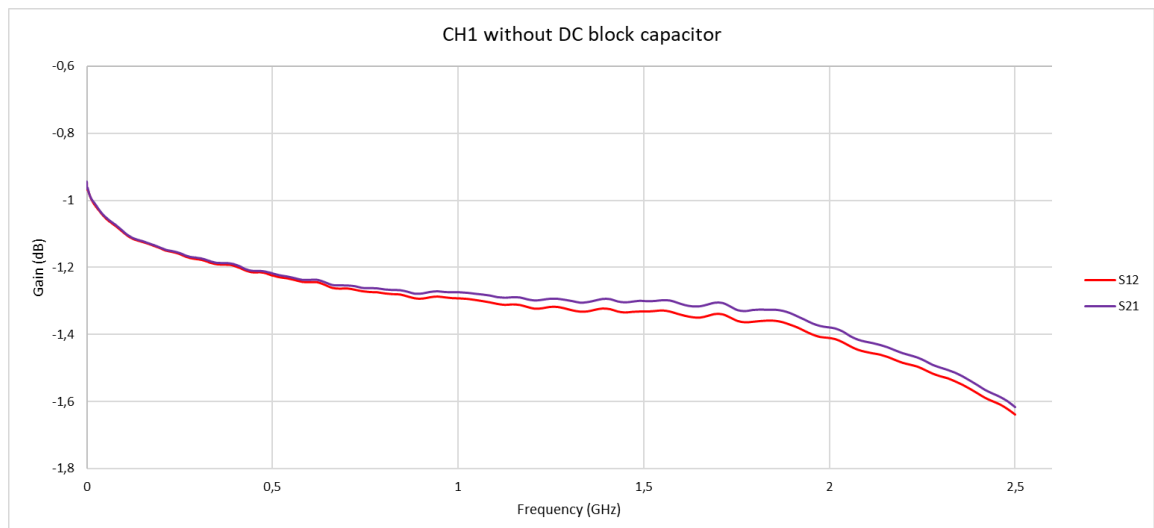


Figure 16. Measurement results on Channel 1 without DC block capacitor

The difference is clearly visible compared to Figure 12 and it does confirm that the large reflection at lower frequencies was due to the DC block capacitors located on the board. It is also clearly visible in Figure 17 that the impedance is around 50 ohms at all point which is the desired results. On the other hand, the difference between the highest and lowest impedance is around 20 ohms, which is not the ideal, but the effect of this behaviour on the gain is possible to compensate mathematically.

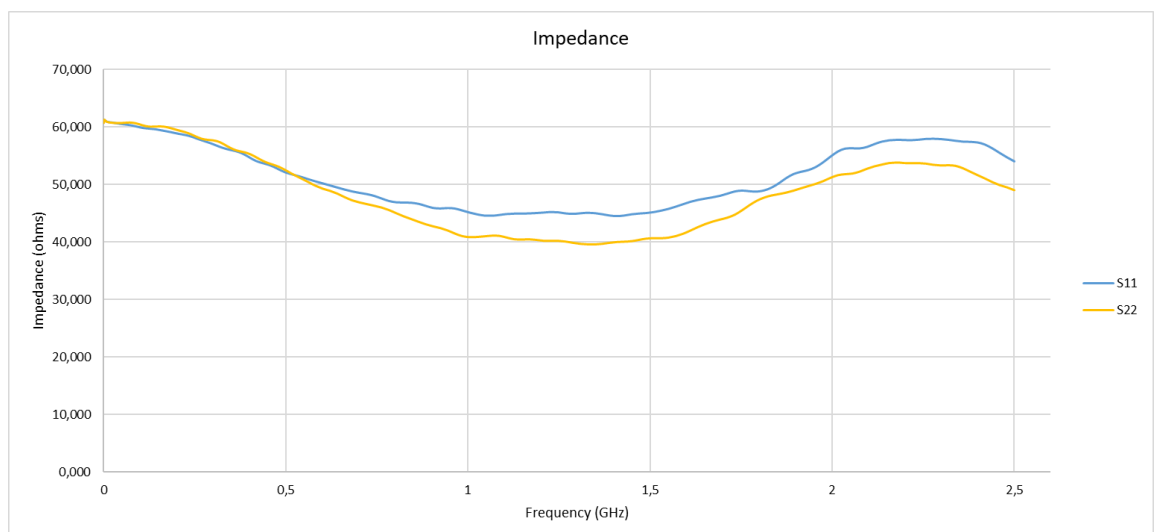


Figure 17. Impedance chart for Board 1 without DC block capacitors

Now that it is clear the gain is constantly in the -3 dB to 3 dB zone which means it is constantly over the half power points and the impedance is around the expected. It is

safe to say, it is possible to use the board in calibration procedures after determining the correction factors and uncertainties when using it.

To determine the correction factors, the results must be converted into linear values first which is done by using equation (10), in which x is the inverse of the gain, since the correction can be simply looked at as the inverse of the error from the nominal which is 0 dB.

$$F_{comp} = 10^{x/10} \quad (10)$$

Figure 18 shows the correction factors for each channel. Applying them means adding the correction factor of the channel used at the specified frequency to the result of the measurement.

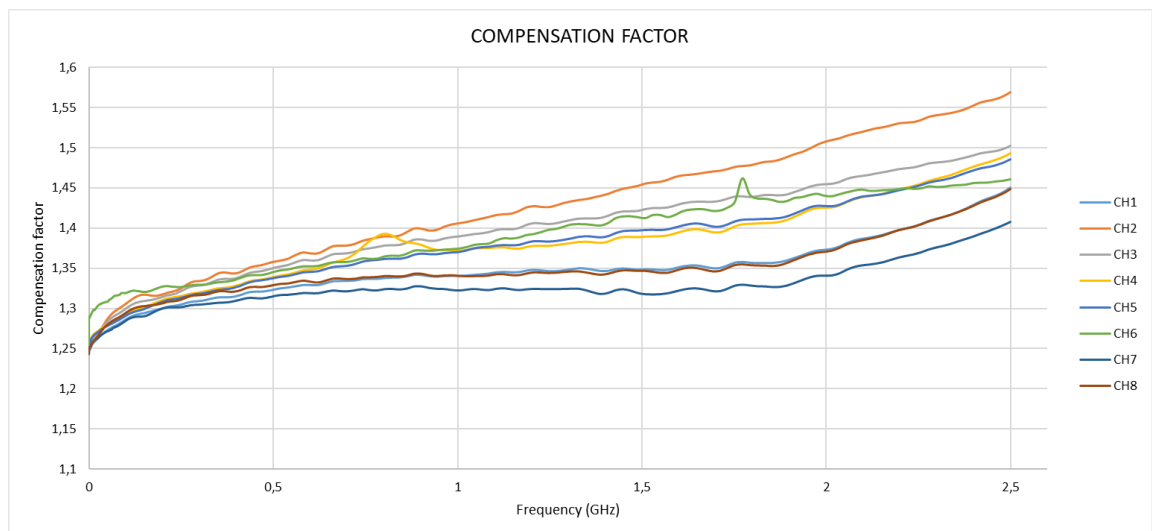


Figure 18. Compensation factors for Board 1

5.3 Measurement Results for Board 2

For the 3.5 GHz board, the same modification of removing the DC block capacitors had to be done and the results are shown in Figure 19. The impedances are shown in Figure 20.



Figure 19. Measurement results on Board 2 for Channel 1

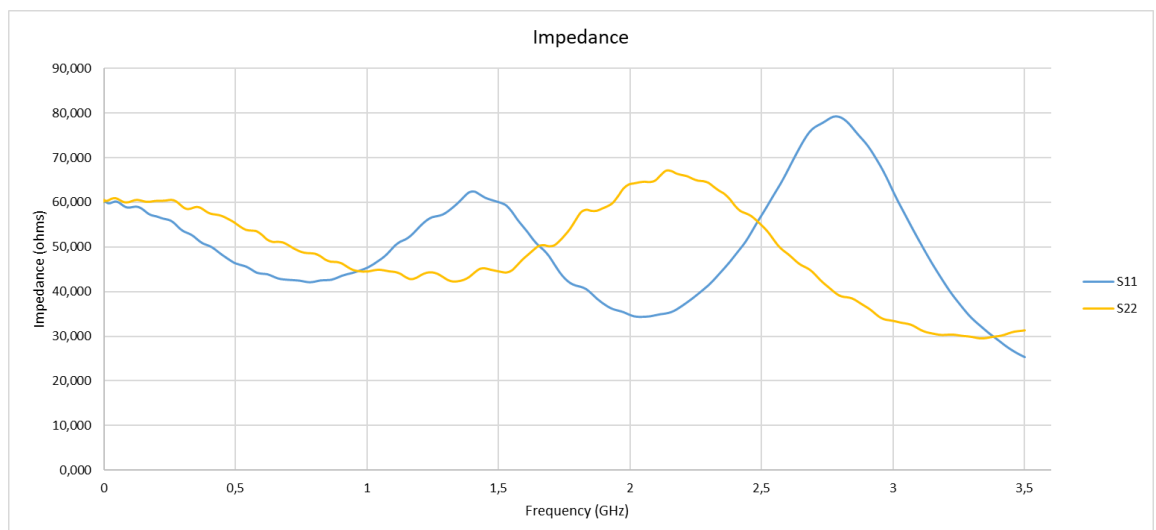


Figure 20. Impedance chart for Channel 1 of Board 2

The compensation factors have been calculated the same way, using equation (10) as for Board 1 and the results can be seen in Figure 21.

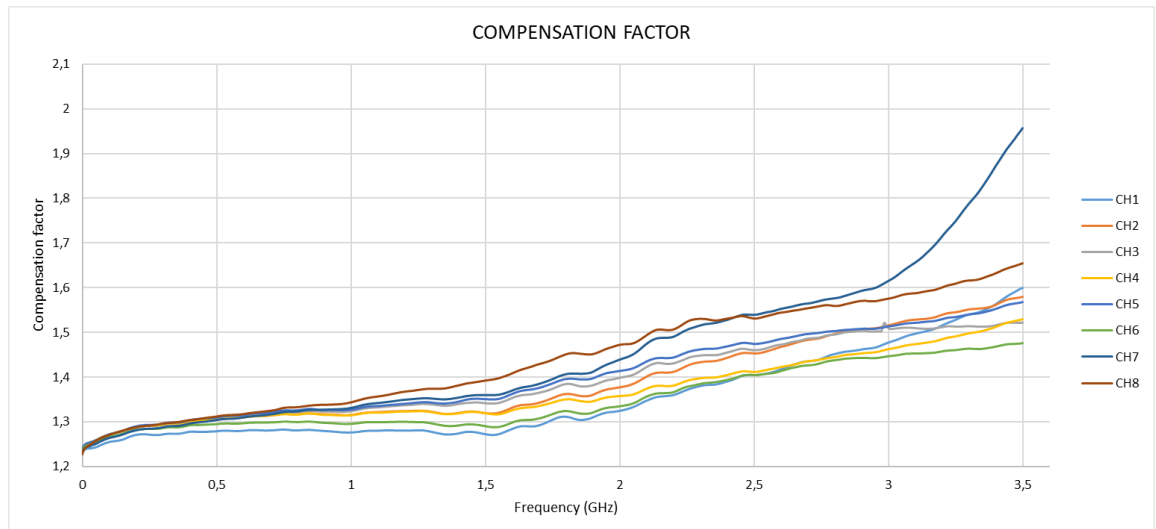


Figure 21. Compensation factors for Board 2

Compared to the others, channel 7 shows a significantly larger correction factor, for which it would be beneficial not to use channel 7 of this board at higher frequencies.

5.4 Uncertainties

During uncertainty calculation, for the specification of the measuring device, Keysight's own calculator sheet was being used, of which the results can be seen in Figure 22.

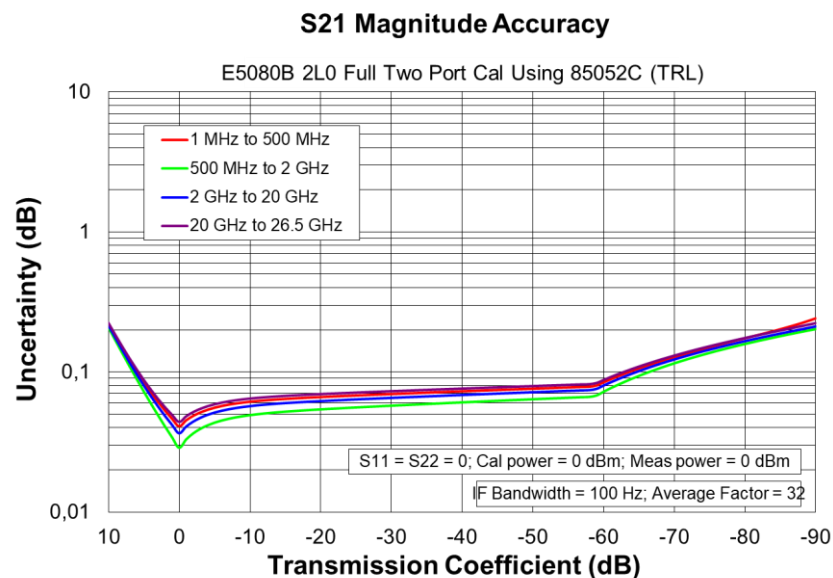


Figure 22. Keysight E5080B uncertainty chart for S21 parameter

Since the reference device, in this case the VNA has been calibrated at the manufacturer, the uncertainty of that calibration geometrically adds onto the

specifications of the device. As an example, up to 100 MHz the uncertainty at 0 dB transmission coefficient provided by Keysight is 0.041 dB and the calibration uncertainty from their laboratory is 0.041 dB, which means applying Equation (1), the combined uncertainty is 0.058 dB. Assuming the uncertainty seen in Figure 22 is already expanded, there is no need to multiply this result with the coverage factor of 2. Applying this uncertainty to our measurement results gives the range in which the results could possibly be. The gains with the combined uncertainties can be seen in Figure 23 for Board 1 and Figure 24 for Board 2.

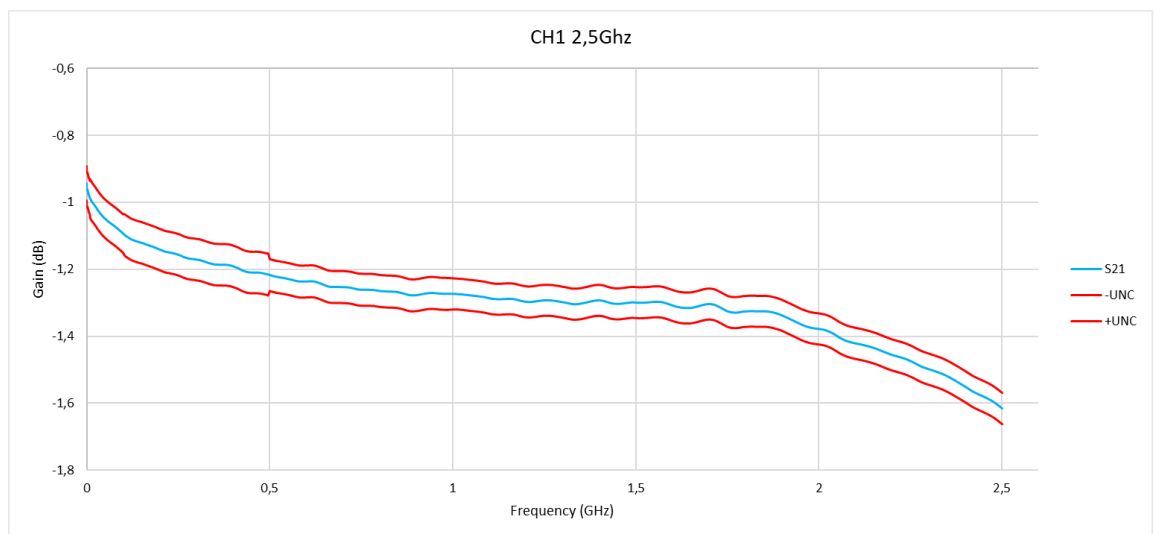


Figure 23. Gain with uncertainties for Board 1

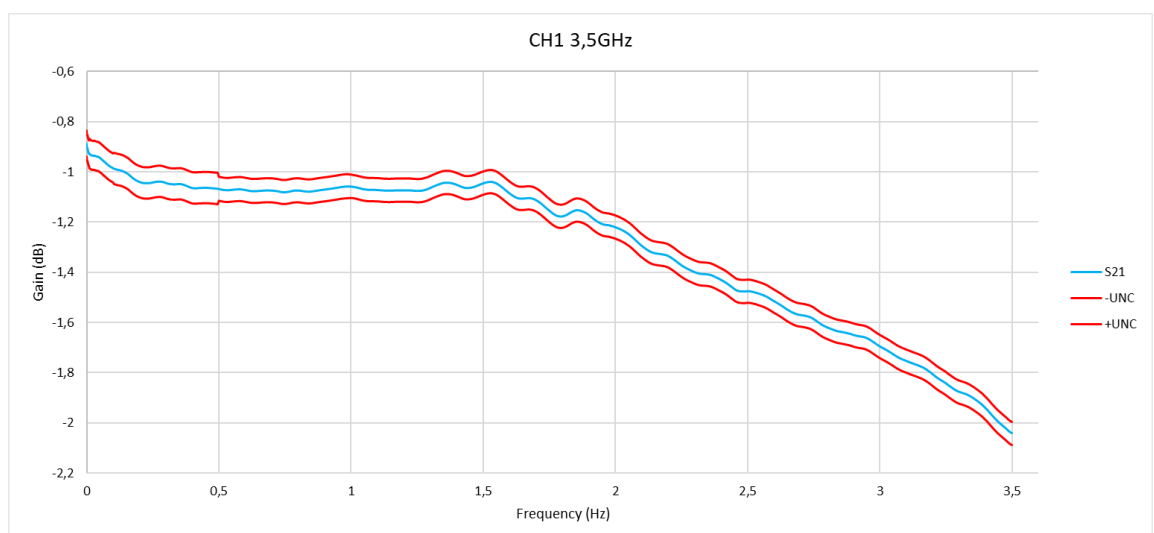


Figure 24. Gain with uncertainties for Board 2

6 Discussion

The results clearly show that both boards are usable for calibration, but they need to be compared to determine the differences and which one is more optimal for which range in the final implementation.

The comparison is done up to 2.5 GHz since that is the maximum frequency of Board 1. Figure 25 shows the gain comparisons for channel 1 of each board.

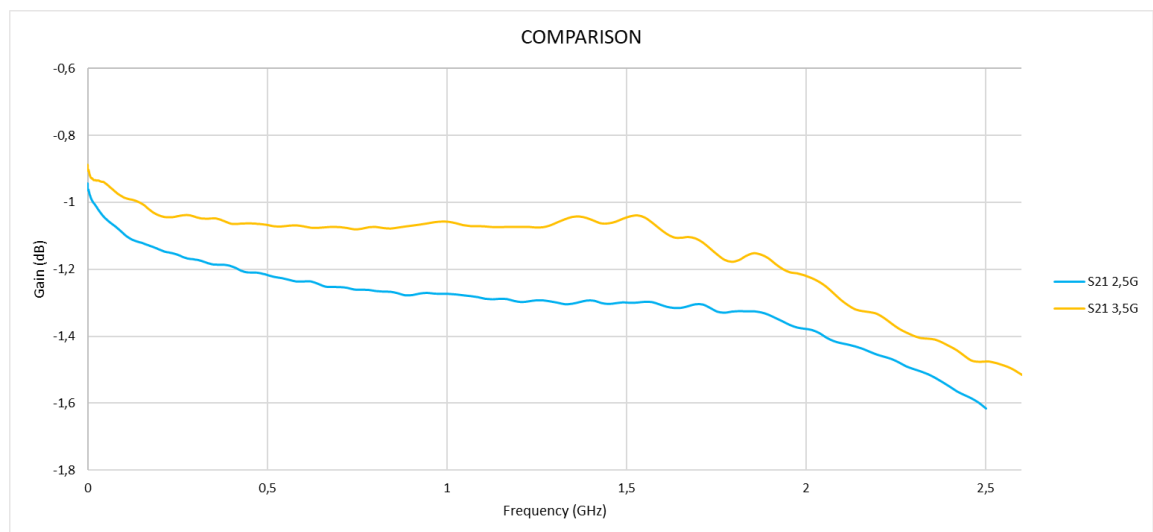


Figure 25. Comparison of gain from port 1 to port 2

Based on Figure 25, at all frequencies Board 2 has a higher gain than Board 1, meaning that less signal is lost across the board, which makes Board 2 a more ideal candidate.

Taking into consideration that channel 7 of Board 2 is close to not behaving as expected, it should not be used at higher frequencies, but up to the 2.5 GHz point the board with less signal loss should be used, which is Board 2.

7 Conclusions

The thesis has successfully determined that both boards are usable in calibration procedures with the application of the correction factors, but there are several points to take into consideration when deciding how to implement them, such as the frequency ranges, the gain on each channel and impedances.

On the full range of Board 1, which is up to 2.5 GHz, Board 2 behaves better and has higher gain which means that Board 2 is ultimately better at all points, thus it should be used in the final implementation. On the other hand, above 2.5 GHz channel 7 of Board 2 is an outlier and requires a correction of almost doubling the raw results which means it should not be used at high frequency measurements. Since the goal of the project was to implement a device which is capable to be used up to 1 GHz, ultimately the project is a success.

For further use, the boards need to be put in boxes and since oscilloscopes most commonly use BNC connections, and the boards have 3.5 mm connectors, there is a need for a transformer. Terminators for the unused channels might be beneficial as well, to avoid signal loss on them, while stabilizing the impedance of the whole board. This implementation means that all measurements need to be repeated and the new correction factors need to be used when putting them to use.

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