EMC LABORATORY MEASUREMENT EQUIPMENT VALIDATION

Coaxial cable attenuation and antenna system impedance matching

Lappeenranta–Lahti University of Technology LUT

Degree Programme in Electrical engineering, Bachelor's thesis

2025

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Examiners: Paula Immonen

Abstract

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This paper aims to validate and improve the accuracy of electromagnetic compatibility (EMC) laboratory measurement equipment. The accuracy is investigated according to two phenomena, cable losses in coaxial cables and energy reflections caused by impedance mismatch between components in antenna systems. The effects of these phenomena on EMC testing are analysed and measured in this paper. Measuring these phenomena is crucial to ensure adequate testing capabilities and certainty in test results of an EMC laboratory.

The main measurement device used to measure the cable losses and the quality of the impedance matching in antenna systems is an Anritsu-made S331P vector network analyser, which is specially designed for these kinds of measurements. The S331P is capable of measuring the specific cable losses of a coaxial cable along a wide range of frequencies. In the specific EMC laboratory used in the making of this paper, the relevant test frequencies range from 150 MHz to 6 GHz. The S331P outputs precise frequency-dependent attenuation data, which can be used to verify if a cable is faulty and improve the accuracy of future EMC tests done using the cables in question. Accuracy can be improved through loss compensation, in which the lost energy in the cable is added to the EMC test results by the measurement software, improving the accuracy of the test results. As mentioned, the cable loss measurements are not only done to improve the accuracy of test results by cable loss compensation, but also to ensure that each cable is not faulty. Abnormally high losses, which deviate from expected datasheet values, can indicate that the cable is damaged and not suitable for precision testing. One such cable was found during the cable loss measurements done in this paper. The exterior of the cable had no signs of damage, highlighting the importance of the cable loss

measurements. The faulty cable most likely would have continued to be in use due to the lack of external signs of damage.

The impedance matching measurements on antenna systems were done to ensure energy reflections due to mismatch in impedances do not affect EMC measurement accuracy in a significant way. The measurement results proved the impedance matching along the system was at acceptable levels, meaning only minimal reflections occurred, which do not affect measuring accuracy in a significant way. Even though this result was expected, it provides more confidence in the accuracy of future EMC measurements done with the systems, since the actual magnitude of reflections is now known and deemed negligible.

Tiivistelmä

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUTin energiajärjestelmien tiedekunta
Sähkötekniikan koulutusohjelma

Axel Järveläinen

EMC-laboratorion mittauslaitteiston validointi
Koaksiaalikaapelien vaimennukset ja antennijärjestelmien impedanssin yhteensopivuus

Kandidaatintyö

2025

37 sivua, 23 kuvaa, 6 taulukkoa

Tarkastaja: Paula Immonen

Avainsanat: Kaapelihäviöt, Paluuhäviöt, VSWR

Tämän työn tavoitteena on validoida ja parantaa sähkömagneettisen yhteensopivuuden (EMC) laboratoriomittauslaitteiden mittaustarkkuutta. Tarkkuutta tutkitaan kahden ilmiön perusteella: koaksiaalikaapeleiden vaimennuksen ja antennijärjestelmissä esiintyvien impedanssisovituksen virheistä aiheutuvien heijastumien kautta. Näiden ilmiöiden vaikutuksia EMC-testeihin analysoidaan ja mitataan tässä työssä. Näiden ilmiöiden mittaaminen on olennaista riittävien testausvalmiuksien ja mittaustulosten varmuuden varmistamiseksi.

Pääasiallinen mittauslaite, jota käytetään kaapelihäviöiden ja antennijärjestelmien impedanssisovituksen laadun mittaamiseen, on Anritsun valmistama S331P-vektoriverkkoanalysaattori, joka on erityisesti suunniteltu tämänkaltaisiin mittauksiin. S331P kykenee mittaamaan koaksiaalikaapelin taajuuskohtaisia häviöitä laajalla taajuusalueella. Tässä laboratoriossa olennaiset mittaustaajuudet vaihtelevat 150 MHz:n ja 6 GHz:n välillä. S331P mahdollistaa koaksiaalikaapeleiden suorituskyvyn tarkan karakterisoinnin tarjoamalla taajuusriippuvaista vaimennusdataa. Mittaustulosten avulla tulevia EMC-testejä voidaan parantaa tekemällä häviökompensaatioita, mikä parantaa testitulosten tarkkuutta.

Kaapelihäviömittauksia tehdään paitsi testitulosten tarkkuuden parantamiseksi häviökompensaation avulla, myös varmistamaan, etteivät kaapelit ole viallisia. Poikkeuksellisen suuret häviöt, jotka poikkeavat odotetuista valmistajan ilmoittamista arvoista, voivat viitata kaapelin vaurioitumiseen ja siihen, ettei kaapeli sovellu tarkkuustestaukseen. Yksi tällainen viallinen kaapeli löydettiin tämän työn aikana suoritetuissa kaapelihäviömittauksissa. Kaapelin ulkoisessa kunnossa ei ollut näkyviä vaurioita, mikä korostaa kaapelihäviömittausten tärkeyttä.

Antennijärjestelmien impedanssisovituksen mittaukset tehtiin varmistamaan, etteivät impedanssin eroista johtuvat heijastumat vaikuta merkittävästi EMC-mittausten tarkkuuteen. Mittaustulokset osoittivat, että järjestelmän impedanssisovitus oli hyväksyttävällä tasolla, mikä tarkoittaa, että heijastumat ovat vähäisiä eivätkä vaikuta mittaustarkkuuteen merkittävästi. Vaikka tämä tulos oli odotettu, se lisää luottamusta tulevien järjestelmällä tehtävien EMC-mittausten tarkkuuteen. (Suomenkielinen tiivistelmä käänntetty englanninkieliestä käyttäen tekoälyä)

Symbols and abbreviations

Latin characters

R&D	Research and Development	
EMC	Electromagnetic Compatibility	
EMI	Electromagnetic Interference	
EUT	Equipment Under Test	
VSWR	Voltage Standing Wave Ratio	
RF	Radio Frequency	
RL	Return Loss	
γ	Reflection coefficient	
V_{ref}	Reflected voltage	V
V_{in}	Input voltage	V
I_{for}	Forward current	A
I_{ref}	Reflected current	A
$V_{\mathrm{Max}}, V_{\mathrm{Min}}$	Maximum and minimum voltage of standing wave	V

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Abstract

1 Introduction

Electromagnetic compatibility (EMC) testing for electronics is now more prevalent than ever. Ensuring that produced electronic devices do not produce excessive amounts of electromagnetic interference (EMI) and can withstand external EMI are crucial for ensuring reliability and intended function. EMC testing is the convincing way to ensure a device possesses these abilities. Testing methods vary depending on the equipment under test (EUT), but proper measuring conditions and accurate measurement equipment are always required for valid results. The accuracy of measurement equipment has many variables, and in practice, it's impossible to achieve truly accurate results, but getting as close as possible is necessary. Examples of phenomena that can negatively affect testing accuracy are losses in transmission cables and reflections of energy in antenna systems caused by impedance mismatch. These phenomena are explained and measured in this document.

The cable loss measurements are done to ensure the cables used in actual EMC measurements do not have abnormally high losses, which can drastically attenuate measurement results. In this document, the coaxial cable losses are not only measured to weed out defective units, but the exact loss data of each cable is used to compensate for the losses in future official EMC measurements they are used in. The magnitude of a faulty cable can have on test results is demonstrated in this document by simulating an EMI emissions test using a faulty cable found in this paper.

In addition to the measurement and compensation of cable losses, the quality of an EMC test antenna system's impedance matching between its components is measured. This is done to verify that the antenna system used in its different configurations is capable of transmitting the received energy to the measurement device with minimal reflections of energy. The quality of the impedance matching is determined through return loss and VSWR (Voltage standing wave ratio) measurements done in this paper.

Objectives

The goals of this paper were to:

1. measure the attenuation of coaxial cables used in an EMC laboratory to remove defective units and acquire precise attenuation data as a function of frequency.
2. improve measurement accuracy by compensating for cable losses.
3. measure the return loss and VSWR of an EMI emission antenna system to verify adequate impedance matching.

2 Background

This chapter offers a brief introduction to impedance matching, return loss, VSWR and cable losses. This introduction includes the estimation of their magnitude and the reasons they appear. The effects of these phenomena are also explained from the standpoint of EMC testing.

2.1 Return loss

Return loss represents the losses between the sent and returned power, which is based on impedance matching. A mismatch between the impedances of the system components can cause a portion of the signal's power to be reflected back to the source, preventing all of the power from reaching its intended destination. A high return loss is desirable, which equates to a good impedance matching since none or very little of the power is being returned to the source.

From an EMC testing standpoint, measuring EMI emissions usually requires an EMC chamber, a receiving antenna and an EMI receiver connected with coaxial cables. This system is visualised in Figure 1. Each component in the system has its own impedance. Since reflections happen due to impedance mismatches, they can occur at multiple points in the system.

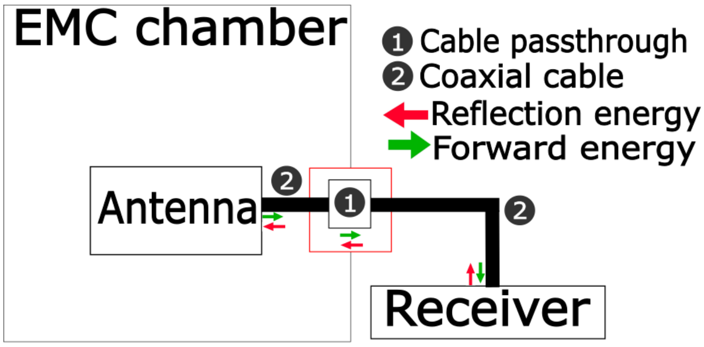


Figure 1: Reflections in an Emission testing setup

The quality of impedance matching between these different components in Figure 1 is determined by how much energy is reflected between each component. High amounts of reflections can cause uncertainty in the final EMC measurement results, since the reflections attenuate the perceived energy at the measurement receiver.

A perfect impedance match between components, causing no reflections, is neither feasible nor necessary. As long as the reflections stay at acceptable levels, they can be neglected. The acceptable return loss levels vary according to the EMC test type, but generally, in an EMI emission antenna system, the acceptable limit is above 7.36 dB, otherwise, the impedance matching can be considered as poor (Smith, 2023).

The magnitude of the return losses can be estimated using the eq. (1), in which return loss is equal to twenty times the tenth-based logarithm of γ (White, 2004).

$$RL = -20\log(\gamma) \tag{1}$$

γ is the reflection coefficient, which is the ratio of the original forward and the reflected wave, shown in eq. (2),

$$\gamma = \frac{V_{\text{ref}}}{V_{\text{in}}} \tag{2}$$

The reflection coefficient γ, depends on the impedance difference between components and can also be estimated separately between each component. Considering the two coaxial cables connected at the passthrough in Figure 1 and Figure 2, the return loss between the cables is derived starting at eg(3). For the sake of clarity, the cable connected to the antenna in Figure 1 and in Figure 2 marked as coaxial cable 1 will be referred to as the first cable. The cable connected to the receiver in Figure 1 and in Figure 2, marked as coaxial cable 2, will be referred to as the second cable.

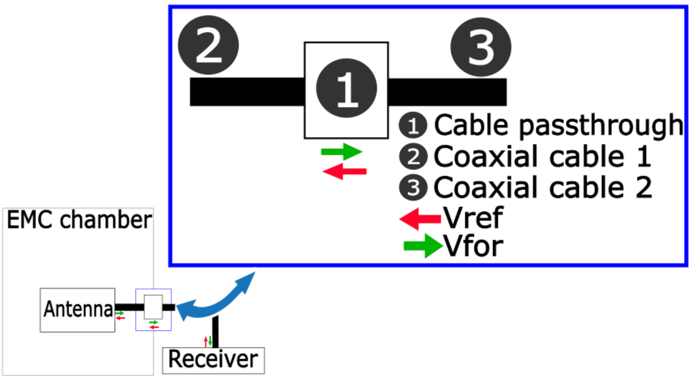


Figure 2: Chamber pass-through block diagram

Using Ohm's law, the equation for the impedance of the second cable is shown in eq (3).

$$Z_2 = \frac{V_2}{I_2} = \frac{V_{\text{for}} - V_{\text{ref}}}{I_{\text{for}} - I_{\text{ref}}} \tag{3}$$

Z_2 is the impedance of the second cable, V_2 is the cable voltage, and I_2 is the cable current. The voltage in the second cable is equal to the original voltage, coming from the first cable, minus the portion that is reflected in the pass-through of the chamber; the same is true for the current. (Teppati, 2013).

The impedance of the first cable can also be determined using Ohm's law. The impedance of the cable is equal to the original input voltage, originating from the antenna, divided by the original input current, eq(4), or reflected voltage divided by reflected current, eq(5). (Teppati, 2013)

$$Z_1 = \frac{V_{\text{for}}}{I_{\text{for}}} \tag{4}$$

$$-Z_1 = \frac{V_{\text{ref}}}{I_{\text{ref}}} \tag{5}$$

From the eq(4) and eq (5), the reflected current I_{ref} and the forward currentI_{for} can be inserted into eq. (3), which results in eq.(6).

$$Z_2 = \frac{V_2}{I_2} = \frac{V_{\text{for}} + V_{\text{ref}}}{\frac{V_{\text{for}}}{Z_1} - \frac{V_{\text{ref}}}{Z_1}} \tag{6}$$

This can be simplified into eq.(7).

$$Z_2 = Z_1 \frac{1 - \frac{V_{\text{ref}}}{V_{\text{for}}}}{1 + \frac{V_{\text{ref}}}{V_{\text{for}}}} \tag{7}$$

Using eq.(2), the voltages in eq.(7), can be turned into the reflection coefficient γ, resulting in eq.(8).

$$Z_2 = Z_1 \frac{1 + \gamma}{1 - \gamma} \tag{8}$$

eq.(8) can be simplified to find reflection coefficient γ as a function of second (Z_2) and first cable (Z_1) impedance.

$$\gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{9}$$

The return loss as a function of impedance, between the two cables, can now be estimated by inserting eq.(9) into eq.(1), resulting in eq.(10).

$$RL = -20\log\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right) \tag{10}$$

From equation 10, the relation between return loss and impedance mismatch is visible. The higher the mismatch, the lower the return loss is.

2.2 VSWR

Similar to return loss, VSWR (Voltage Standing Wave Ratio) is also based on impedance matching. Impedance mismatches between components of an antenna system create reflections in energy, which react constructively and destructively with the original forward wave, creating a standing wave along the system. In the system presented in Figure 1, the standing wave created in the first coaxial cable from Figure 2 is presented in Figure 3.

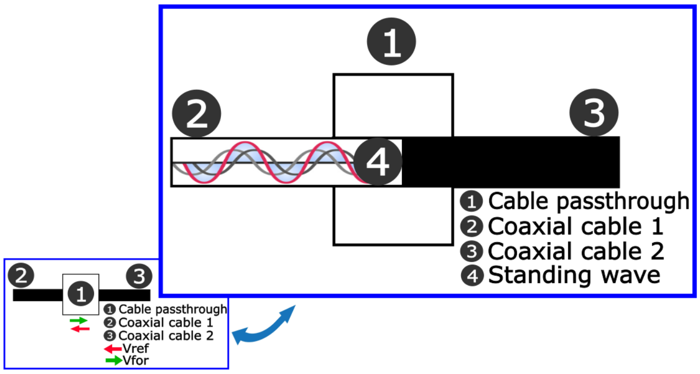


Figure 3: VSWR created in chamber pass-through from reflection

The VSWR is the ratio of the maxima and minima of the created standing wave, which is formed from the forward and reflected waves in the transmission line. The maxima and minima of the combined signal can be estimated with eq. (11) and eq.(12), in which V_{for} is the forward voltage and γ the reflection coefficient (White, 2004).

$$V_{\mathrm{Max}} = V_{\mathrm{for}} \left(1 + \gamma\right) \tag{11}$$

$$V_{\mathrm{Min}} = V_{\mathrm{for}} \left(1 - \gamma\right) \tag{12}$$

The eq. (11) and eq.(12) can be formed into eq.(13).

$$\frac{V_{\mathrm{Max}}}{V_{\mathrm{Min}}} = \frac{1+\gamma}{1-\gamma} \tag{13}$$

Since the VSWR is the ratio of the maxima and minima of the standing wave, eq.(13) is equal to eq(14).

$$\mathrm{VSWR} = \frac{1+\gamma}{1-\gamma} \tag{14}$$

Using eq.(9) definition for γ, the VSWR in eq.(14) can be expressed as eq(15) using the system component impedances, in this case, coaxial cable 1 and 2 from Figure 3.

$$\mathrm{VSWR} = \frac{1 + \frac{Z_2 - Z_1}{Z_2 + Z_1}}{1 - \frac{Z_2 - Z_1}{Z_2 + Z_1}} \tag{15}$$

The VSWR is similar to the return loss, both can be used to describe the quality of impedance matching in a system.

2.3 Mismatch error and Measurement uncertainty

Mismatch error is the uncertainty caused by reflections in the measurement system, which is directly linked to the impedance matching quality. The magnitude of the mismatch loss can be estimated using eq.(16), in which γ is the reflection coefficient. (White, 2004)

$$\text{Mismatch loss (dB)} = -10log(1-\gamma^2) \tag{16}$$

Good EMC testing practices include uncertainty magnitude assessment in test results. Some standards and test specifications limit the maximum measurement uncertainty. I.e, TechSpec Methods of measurement and limits for EMC emissions require the radiated emissions test uncertainty to follow limits given in Table 1.

Table 1: Maximum measurement uncertainty (TechSpec, Release 17, Table 3B)

Parameter	**Uncertainty**
Effective radiated RF power between 30 MHz and 180 MHz	±6 dB
Effective radiated RF power between 180 MHz and 12.75 GHz	±3 dB

This means the maximum allowed uncertainty has to be below ±6 or ±3 dB, depending on the frequency range. These limits include all measurement uncertainties in the system, meaning the mismatch loss is included.

If the total uncertainty is over the limits, TechSpec has stated that, “Any additional uncertainty in the Test System over and above that specified in Table 3B is used to tighten the Test Requirements, making the test harder to pass. This procedure will ensure that a Test System not compliant with Table 3B does not increase the probability of passing an EUT that would otherwise have failed a test if a Test System compliant with Table 3B had been used.”

The return loss and VSWR measurements done later in this paper are to asses the mismatch loss magnitude, which adds more information to the actual EMC measurement results about the total uncertainty.

2.4 Cable loss

When electrical energy is transmitted through a coaxial cable, some energy is always lost. The magnitude of the losses has many variables. However, the reason for most of the losses resulting in signal attenuation in coaxial cables originates from resistive losses. The centre of the cable conducting the signal is usually made of copper. Conductive materials have resistance, which converts some of the energy into heat. These losses increase with frequency due to the skin effect, which limits the area of the conductor through which the current flows. This is more relevant since the frequencies used in EMC tests can be as high as 6 GHz.

In this specific EMC laboratory used in the making of this paper, every test done inside the EMC chamber used coaxial cables to transmit energy. Since the coaxial cables have losses, they affect all tests in one way or another. From an EMI emission testing perspective, verifying that the cables used are healthy and compensating for cable losses is crucial. A faulty coaxial cable with high losses can drastically lower the perceived emission levels. Losses in cables attenuate the perceived levels of EMI emitted by an EUT. The negative effect of cable attenuation is not exclusive to emission tests, it can lead to an EUT falsely passing many different EMC tests by lowering results or test intensity.

To prevent cable losses from affecting test results, the cable needs to be compensated for. This requires precise attenuation data as a function of frequency, which can be used to enhance test accuracy by the measurement software. This data can be acquired from the cable's datasheet or by measuring the actual losses of the cable, the latter being more accurate. Precise cable loss measurements and compensations are done later in this paper.

3 Measurement Setups and Equipment

This chapter includes the following:

- Measurement setup for the VSWR and return loss measurements used to assess the impedance matching quality of EMC laboratory emission antenna systems.
- Measurement setup for the coaxial cable loss measurements, used to identify faulty cables and to obtain attenuation data for cable loss compensation.
- Introduction to the main measurement device used in the tests mentioned above.

3.1 S331P measurement device

The main measurement device of this paper is the Anritsu-made S331p. This device is used to measure the VSWR and return loss of the antenna system following the steps in Section 3.2. The cable loss measurements are also done using this device, following the steps in Section 3.3. Internal calibration of the S331P measurement device was done before every measurement. Calibration was done following the steps given by the manufacturer. (Anritsu Company, 2024)

The reflection magnitude uncertainty according to the device datasheet provided by the manufacturer is presented in Figure 1. The possible error fluctuates according to the measured reflection and the model. The model used in this paper is the 6 GHz version, meaning that in this paper, only the red curve in Figure 4 is relevant.

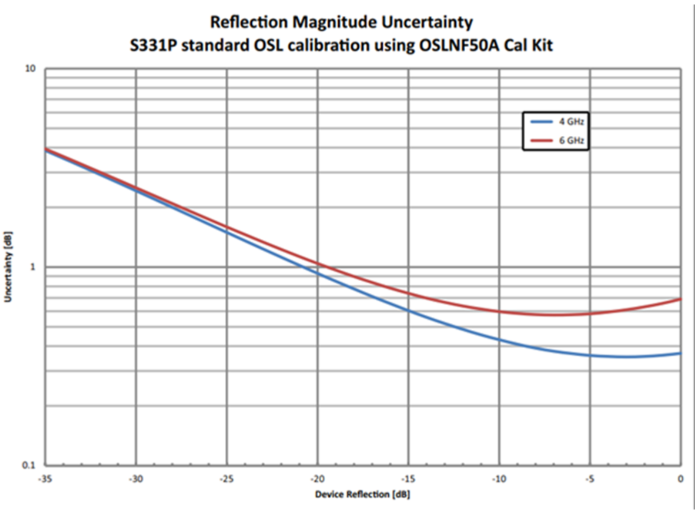


Figure 4: Reflection Magnitude Uncertainty of S331P (Anritsu Company, 2024)

3.2 VSWR and Return Loss setup and EUT

The antenna system under test in this document is presented in Figure 5. The system consisted of an antenna inside an EMC chamber, which was connected to the chamber pass-through using a coaxial cable. Outside, the measurement device S331P was connected to the same pass-through using a coaxial cable.

To measure the return losses of the whole antenna system, the S331P was connected in place of the RF receiver at the end of the system. This way, any reflections that might happen in the cable connections to the antenna or the chamber pass-through would be seen in the results. The antenna's characteristics and the laboratory practices determine the measurement frequency range used. The three different antennas that were tested in this document are listed in Table 2.

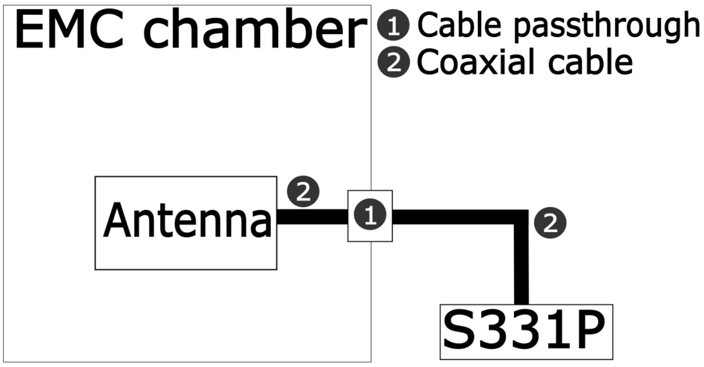


Figure 5: VSWR and Return Loss measurement setup block diagram

Table 2: Return loss and VSWR antenna EUTs

Antenna name and model	**Operating frequency**
VUSLP 9111B - Log Periodic Antenna	200–3000 MHz
VHBB 9124 Biconical Antenna	30–300 MHz
BBHA 9120 J - Double-Ridged Broadband Horn Antenna	0.8–6.2 GHz

3.3 Cable loss setup and EUT

The measurement setup used to measure the cable losses in coaxial cables is presented in Figure 6. The cable under test is connected to the S331P measurement device and a short. The frequency range used for the measurement corresponds to the typical use of the cables in the laboratory, from 0.15 MHz to 6 GHz.

Figure 6: Cable loss measurement setup block diagram

The cable loss measurements were conducted on all cables in use at the EMC laboratory. However, the measurement results of the two cables are only presented in this document. Information about the cables tested in this document is presented in Table 3.

Table 3: EUT – Coaxial cable losses

Cable	**Length**	**Attenuation (Reference Length)**	**Operating Frequency**
EcoFlex 10 Plus	3 m	Measured for 100 m cable: – 1 GHz: 13.49 dB (max)	Up to 8 GHz
HUBER+SUHNER SUCOFLEX 100	3 m	Not specified	Up to 18 GHz

4 Return loss and VSWR measurement results

This section contains the VSWR and return loss measurement results acquired by following the steps presented in Section 3.2.

4.1 The VULP 9118 A - Log Periodic Antenna

The antenna system configuration using the VULP 9118 A log periodic antenna has a VSWR peak of approximately 1.8:1, presented in Figure 7. This corresponds to a return loss of approximately 10.881 dB, presented in Figure 8.

A VSWR of 1.8:1, means the reflection coefficient is

$$\text{VSWR} = \frac{1+\gamma}{1-\gamma} \tag{14}$$

$$1.8 = \frac{1+\gamma}{1-\gamma}$$

$$\gamma = 0.286$$

A reflection coefficient of 0.286 equals a mismatch loss of 0.370 dB, which is the uncertainty caused by reflections to actual EMC measurement results done using this antenna system. A mismatch loss of 0.370 dB is minimal.

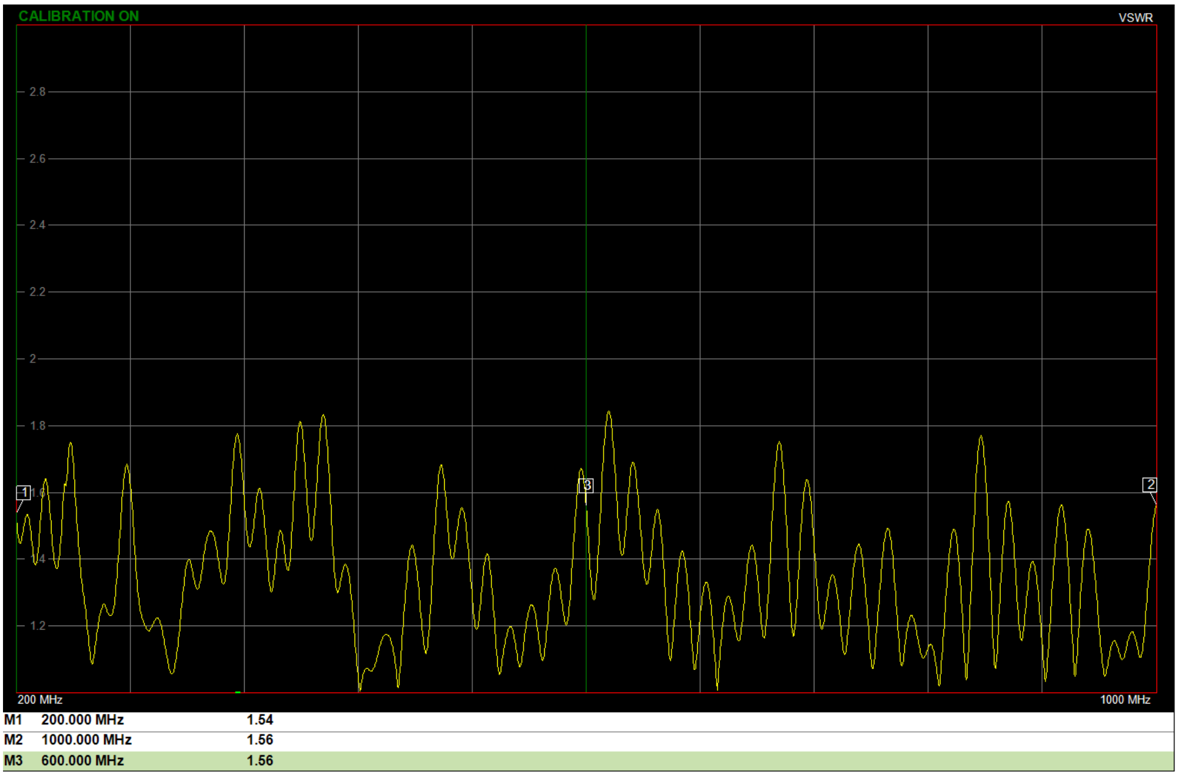
However, this result does not take into account the measurement uncertainty presented in Figure 4. A measured return loss of 10.881 dB equals to a measurement uncertainty of approximately 0.6 dB. The uncertainty is subtracted from the measured return loss to calculate the worst-case scenario.

$$RL = -20\log(\gamma) \tag{1}$$

$$10.881\,\text{dB} - 0.6\,\text{dB} = -20\log(\gamma)$$

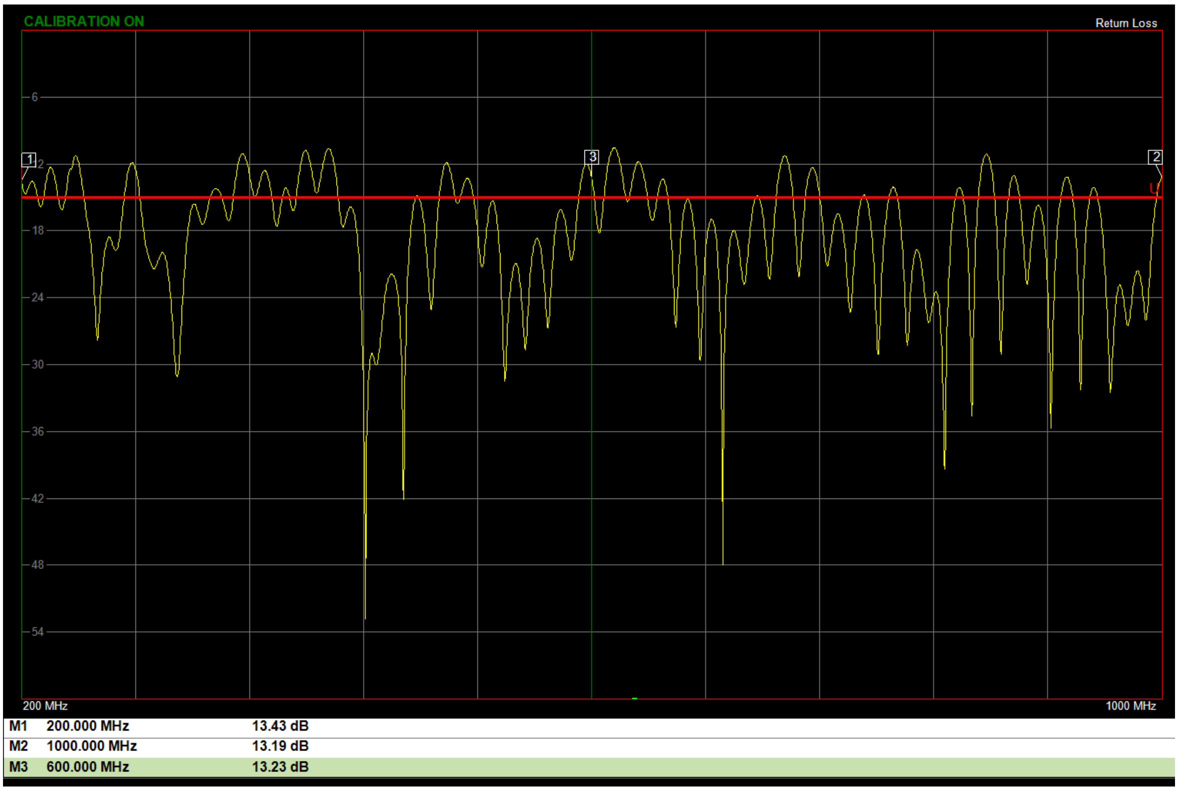
$$\gamma = 0.306$$

The reflection coefficient, including measurement uncertainty, is 0.306. This equals to a mismatch loss of 0.43 dB, which is still minimal.



M1	200.000 MHz	1.54
M2	1000.000 MHz	1.56
M3	600.000 MHz	1.56

Figure 7: VSWR results of VULP 9118 A - Log Periodic Antenna



M1	200.000 MHz	13.43 dB
M2	1000.000 MHz	13.19 dB
M3	600.000 MHz	13.23 dB

Figure 8: Return loss results of VULP 9118 A - Log Periodic Antenna

4.2 BBA 9106 biconical antenna

The antenna system configuration using the BBA 9106 biconical antenna has a VSWR peak of approximately 2.3:1, presented in Figure 9. This corresponds to a return loss of approximately 8.091 dB, presented in Figure 10.

A VSWR of 2.3, means the reflection coefficient is

$$\mathrm{VSWR} = \frac{1+\gamma}{1-\gamma} \tag{14}$$

$$\gamma = \frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1} = 0.394$$

A reflection coefficient of 0.394 equals a mismatch loss of 0.732 dB, which is the uncertainty caused by reflections to actual measurements done using this antenna system. However, this result does not take into account the measurement uncertainty presented in Figure 4.

A measured return loss of 8.091 dB equals to a measurement uncertainty of approximately 0.6 dB. The uncertainty is subtracted from the measured return loss to calculate the worst-case scenario.

$$RL = -20\log(\gamma) \tag{1}$$

$$8.091\,\mathrm{dB} - 0.6\,\mathrm{dB} = -20\log(\gamma)$$

$$\gamma = 0.442$$

The reflection coefficient, including measurement uncertainty, is 0.442. This equals to a mismatch loss of 0.94 dB.

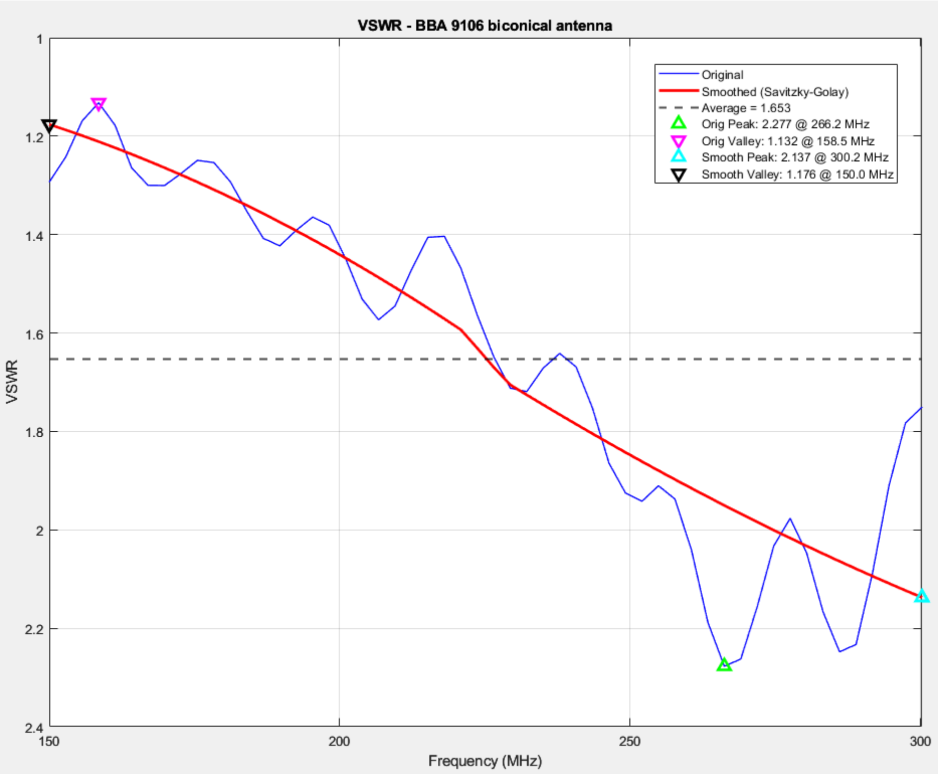


Figure 9: VSWR results of BBA 9106 biconical antenna

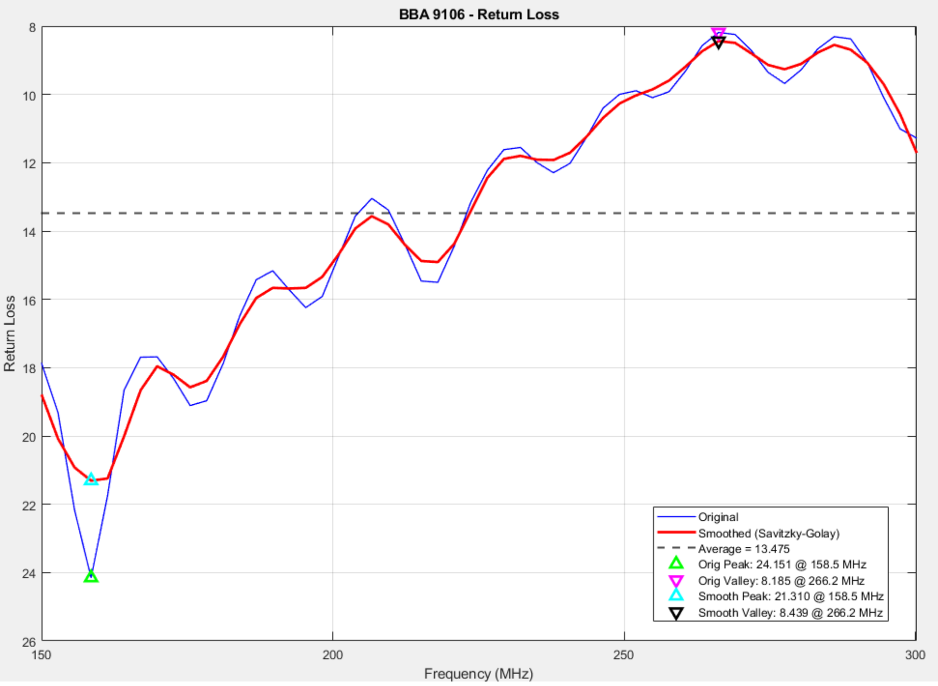


Figure 10: Return loss results of BBA 9106 biconical antenna

4.3 BBHA 9120 LF - Double Ridged Broadband Horn Antenna

The antenna system configuration using the BBHA 9120 LF Double Ridged Broadband Horn Antenna has a VSWR peak of approximately 2.65:1, presented in Figure 11. This corresponds to a return loss of approximately 6.896 dB, presented in Figure 12

A peak of 2.65 VSWR means the reflection coefficient is

$$\mathrm{VSWR} = \frac{1+\gamma}{1-\gamma} \tag{14}$$

$$\gamma = \frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1} = 0.452$$

A reflection coefficient of 0.452 equals a mismatch loss of 0.993 dB, which is the uncertainty caused by reflections to actual measurements done using this antenna system. This result has high amounts of ripple due to the high frequencies. The average peak in VSWR is around 1.98. Due to the high ripple in the results, the average will be used in the assessment.

An average peak of 1.98 VSWR means the reflection coefficient is

$$\mathrm{VSWR} = \frac{1+\gamma}{1-\gamma} \tag{14}$$

$$\gamma = \frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1} = 0.329$$

A reflection coefficient of 0.329 equals a mismatch loss of 0.497 dB, which is the uncertainty caused by reflections to actual measurements done using this antenna system. However, this result does not take into account the measurement uncertainty presented in Figure 4.

A measured return loss of 9.660 dB equals to a measurement uncertainty of approximately 0.6 dB. The uncertainty is subtracted from the measured return loss to calculate the worst-case scenario.

$$RL = -20\log(\gamma) \tag{1}$$

$$9.660\,\mathrm{dB} - 0.6\,\mathrm{dB} = -20\log(\gamma)$$

$$\gamma = 0.352$$

The reflection coefficient, including measurement uncertainty, is 0.352. This equals a mismatch loss of 0.574 dB.

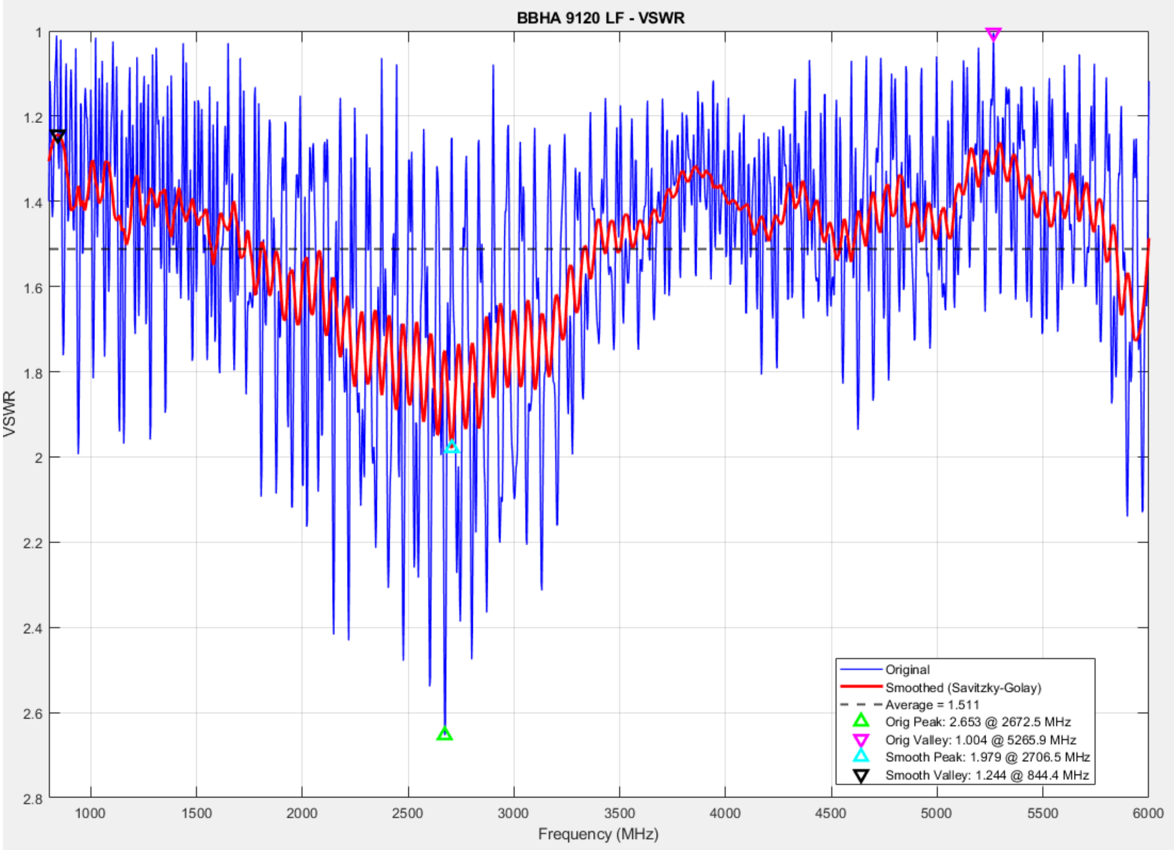


Figure 11: VSWR results of BBHA 9120 LF Double Ridged Broadband Horn Antenna

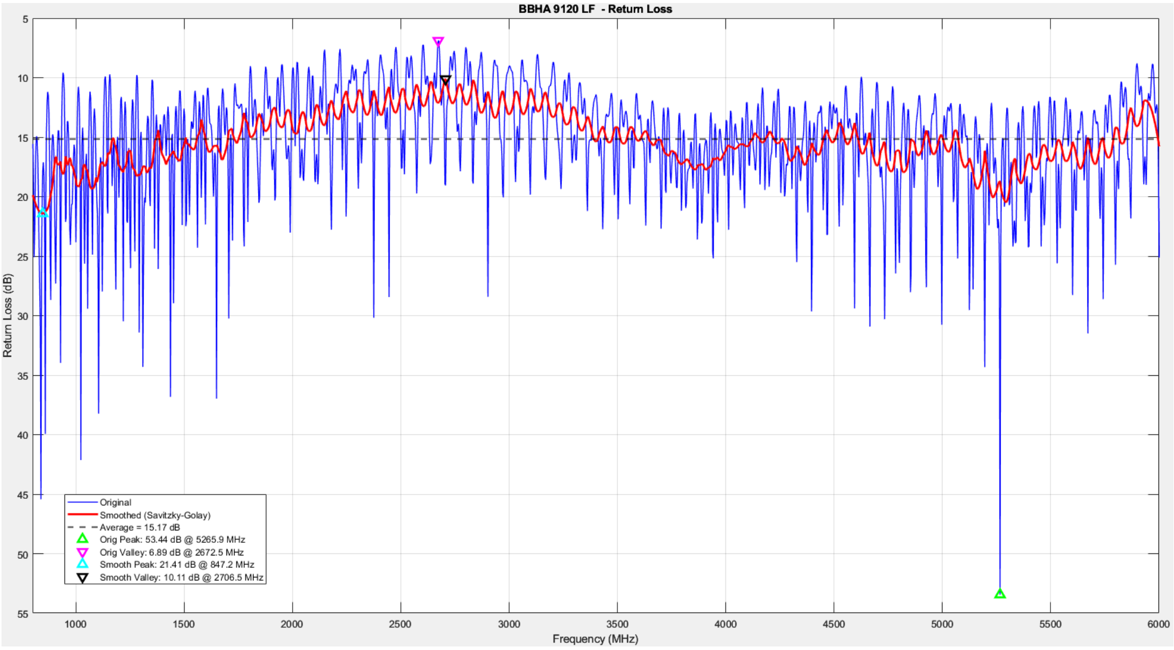


Figure 12: Return loss results of BBHA 9120 LF Double Ridged Broadband Horn Antenna

4.4 Return loss and VSWR measurement summary

The return loss and VSWR measurement results, including measurement uncertainty, are presented in Table 4.

Table 4: Antenna Return Loss and VSWR Measurements

Measurement	Peak Return Loss (dB)	Peak VSWR	Peak Mismatch (dB)
VULP 9118 A	10.881	1.8	0.43
BBA 9106	7.092	2.3	0.944
BBHA 9120 LF	**AVG** 9.07	**AVG** 2.086	**AVG** 0.574

The peak mismatch values can be used when determining the total uncertainty in official EMC test results. Unless otherwise compensated for, the mismatch would be subtracted from the allowed total uncertainty, i.e Table 1.

The BBA 9106 and BBHA 9120 LF VSWR peaks were somewhat high, the preferred VSWR is around 2:1. However, some of the mismatch might be corrected by the actual measurement receiver used in EMC tests, which contains the calibration file for the antenna.

The overall average results are presented in Table 5. The overall mismatch is minimal, meaning the overall impedance matching in the systems is acceptable. A VSWR below 2.5:1 is generally acceptable for EMC testing. Above 2.5:1, the impedance matching along the system can be considered poor. (Smith, 2023)

Table 5: Average Return Loss and VSWR Measurements – (Without measurement uncertainty)

Measurement	AVG Return Loss (dB)	AVG VSWR	AVG Mismatch (dB)
VULP 9118 A	13.23	1.558	0.212
BBA 9106	13.476	1.653	0.271
BBHA 9120 LF	15.17	1.5	0.177

5 Cable loss measurement results

This section contains two cable loss measurement results acquired by following the steps presented in Section 3.3.

5.1 HUBER+SUHNER SUCODLEX 100

In Figure 13, the cable losses of a 3 meter long HUBER+SUHNER SUCODLEX 100 coaxial cable are presented as a function of frequency.

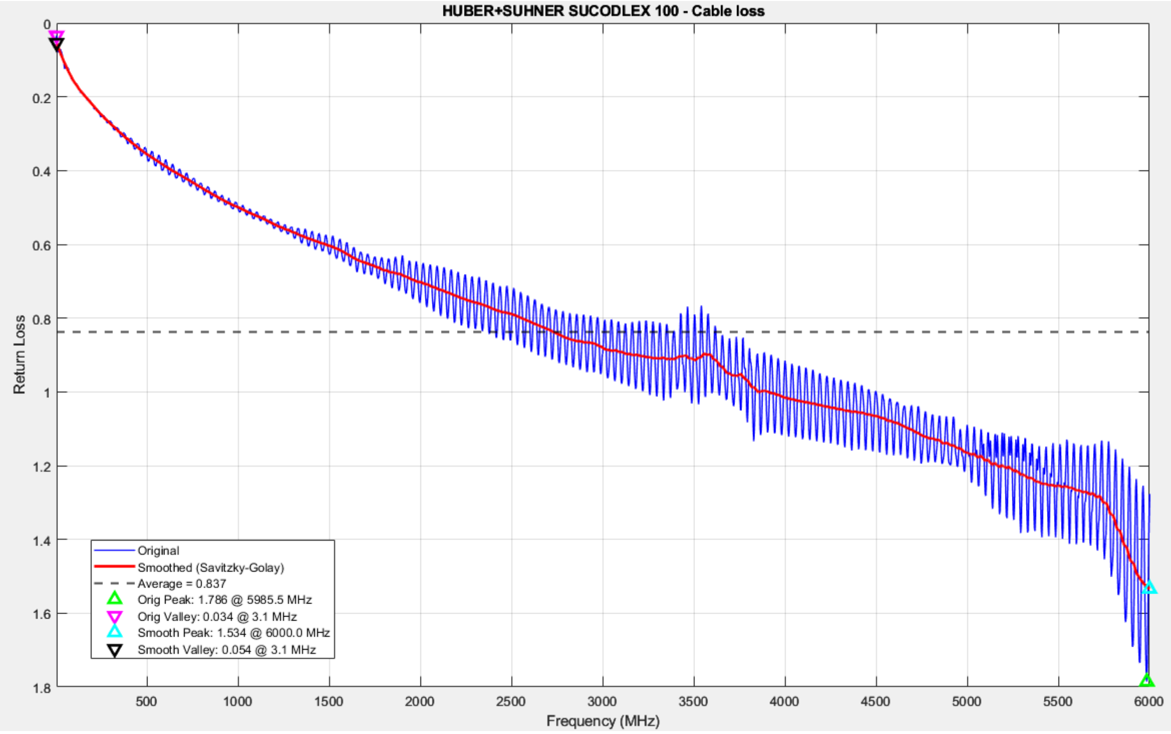


Figure 13: 3m HUBER+SUHNER SUCODLEX 100 - Coaxial cable losses measurement

In the HUBER+SUHNER SUCODLEX 100 cable highest attenuation is 1,79 dB. This serves as a great example of attenuation in healthy coaxial cable, the losses are minimal and stable. The average attenuation across the whole frequency range is 0.84 dB. This may seem neglectable but some EMC test systems may need numerous cables. Even if each cable has minimal losses, these can accumulate to an unacceptable level.

5.2 EcoFlex 10 Plus

In Figure 14, the cable losses of a 3 meter long EcoFlex 10 Plus coaxial cable are presented as a function of frequency.

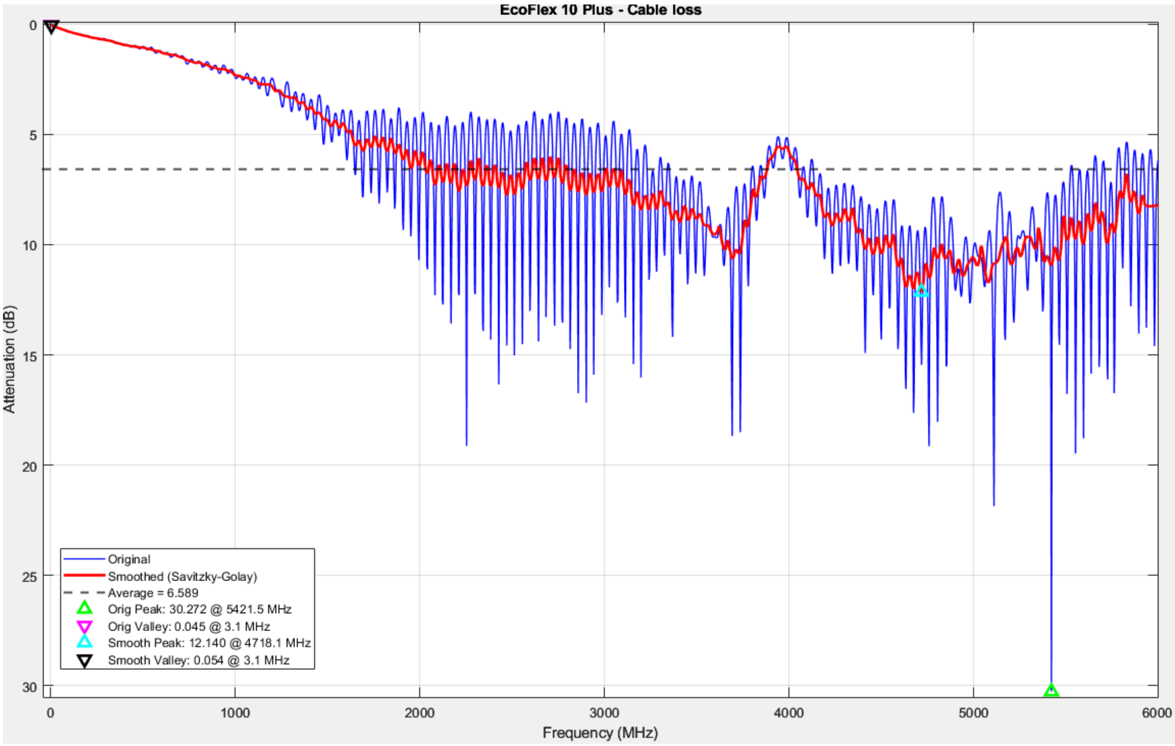


Figure 14: 3m EcoFlex 10 Plus - Coaxial cable losses measurement

In the EcoFlex 10 Plus cable highest attenuation is 30.27 dB, which is only a singular point. However, the overall attenuation of the cable is nowhere near acceptable levels. This measurement was conducted multiple times, resulting in similar attenuation, meaning the cable is faulty.

Using the datasheet reference value, its possible to adjust the ratio to estimate what the cable loss should be at its maximum in the 3 m cable.

$$\frac{\text{DataSheetLength}}{\text{AdjustedLength}} = \frac{\text{DataSheetAttenuation}}{\text{AdjustedAttenuation}} \tag{17}$$

$$\frac{100}{3} = \frac{13.39}{\text{AdjustedAttenuation}} \tag{18}$$

$$\text{AdjustedAttenuation} = 0.4047\,\text{dB} \tag{34}$$

The difference between the calculated and the measured attenuation at the reference frequency is 2.0353 dB. This, however, is nowhere near the levels of even higher frequencies. The attenuation becomes larger and more unstable the higher the frequency is.

Visual inspection of the cable indicates no structural damage which could cause the high attenuation. Cable connectors, presented in Figure 15, have no visible damage either. The cable most likely has internal damage from mechanical shock. This finding highlights the importance of measuring cable losses in coaxial cables, without this measurement, this cable could still be in use since there are no visible problems. The high levels of attenuation this cable has would drastically affect measurement results.

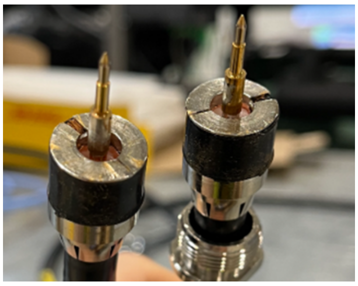


Figure 15: EcoFlex 10 Plus coaxial cable connectors

5.3 Cable loss measurement summary

Table 6: Cable Loss Measurements

EUT - Coaxial cable	**Avg. Attenuation (dB)**	**Losses**	**OK/Faulty**
EcoFlex 10 Plus	6.59	High	Faulty
HUBER+SUHNER SUCODLEX 100	0.84	Low	OK

EcoFelex 10 Plus coaxial cable possessed abnormally high losses and was deemed faulty and decommissioned. This was an unexpected discovery, since the cable in question had no external signs of damage.

The HUBER+SUHNER SUCODLEX 100 had expected low attenuation. The frequency-specific attenuation data were saved and used to compensate for the minimal losses in future EMC tests, in which this cable will be used.

6 Demonstration of cable losses effect on EMC testing

This section contains a demonstration of the effects a faulty cable can have on EMC testing.

6.1 Background for the test

In this section, the impact of a high-loss coaxial cable on measurement results is demonstrated by simulating an actual EMI emissions test. The emission test is performed using both cables discovered during the cable loss measurements in Section 5. The high-loss EcoFlex 10 Plus and the low-loss HUBER+SUHNER SUCODLEX 100 coaxial cable information is presented in Table 6.

The expected results from this demonstration are that the EMI emission measurements done using the high-loss cable are lower compared to results acquired using the low-loss cable. This means the high-loss cable would attenuate the perceived EMI emissions radiated from an actual EUT, leading to false EUT performance data and possibly even falsely passing the test. The impact of the faulty cable will be evaluated by comparing the measurement results obtained with these cables.

The setup used in the demonstration is presented in Figure 16, is an actual EMI emission test setup. Two measurements were taken in which the EUT cable, in Figure 16, was the EcoFlex 10 Plus, and in the other, the HUBER+SUHNER SUCODLEX 100. The EUT cable is connected to the chamber pass-through and the antenna receiving the EMI. Outside the chamber, a low-loss coaxial cable, whose losses are automatically compensated for, connects the chamber pass-through to the measurement receiver.

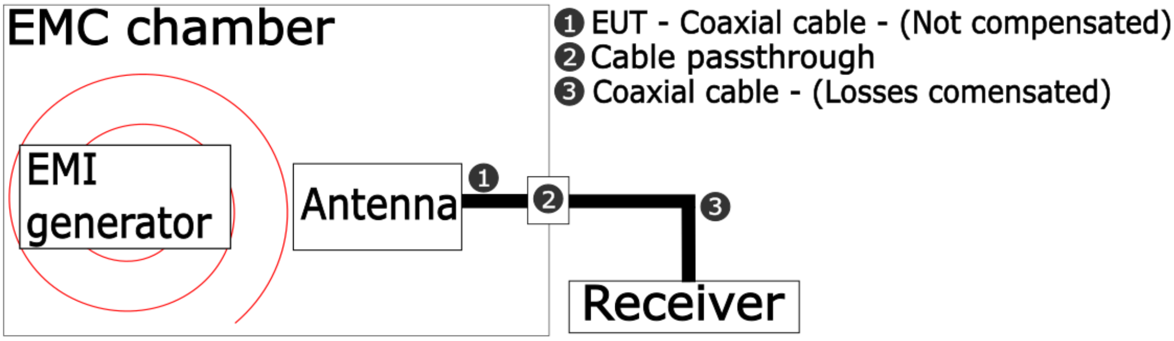


Figure 16: Verification test block diagram

The EMI generator inside the chamber is a Teseq-made RSG 3000, which is a reference spectrum generator. The RF generator used can produce signals as high as 6 GHz, but the emitting antenna used with the generator was capable of reaching only 2.8 GHz. This means the effect of the faulty cable in this paper can only be reliably demonstrated to 2.8 GHz.

6.2 RF reference emitter

The RSG 3000 is a reference spectrum generator for the frequency range of 1 MHz up to 6 GHz. The typical output level, according to the manufacturer, is presented in Figure 19. The generator was set to 10 MHz intervals, meaning at 2 GHz, the output level is around 72 dbµV. (Teseq, 2011)

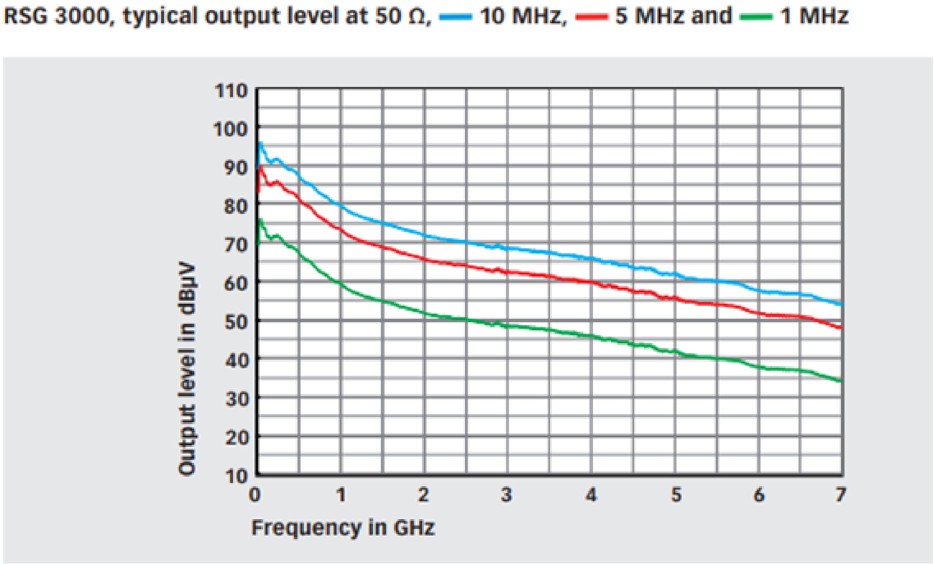


Figure 17: RSG 3000 output (Teseq, 2011)

6.3 Receiver antenna

A Schwarzbeck BBHA 9120 LF broadband horn antenna was used during the comparison test to measure the RSG 3000 reference emitter signal. The measurement software is compatible with the antenna itself, meaning all of the antenna characteristics that would affect the measurement results are taken into account by the software.

6.4 Cable loss demonstration results

In this chapter, the measurement results of the tests explained in Chapter 6.1 are presented and interpreted.

The EMI emissions test results using the low-loss HUBER+SUHNER SUCODLEX 100 coaxial cable are presented in Figures 18 and 19. The green limit line visible in Figure 18 is a pass limit for a certain emission test class. The measured EMI level is considerably over the passing limit at around 2 GHz and 2.5 GHz. If this were an official EMI emissions test, the result would be a fail.

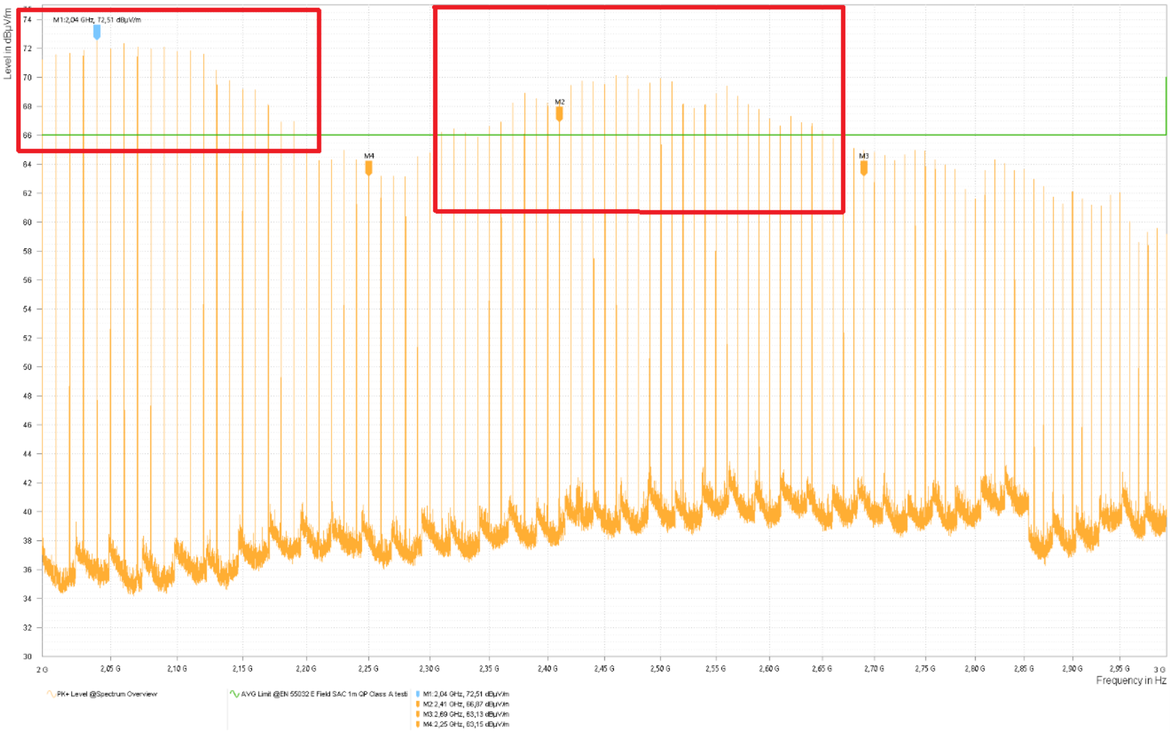
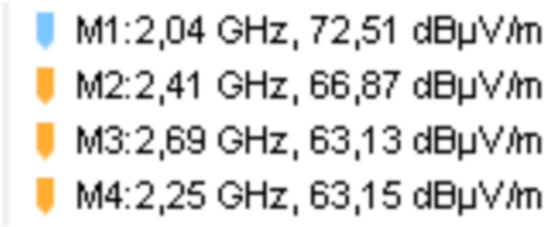


Figure 18: RF reference emitter noise measurement using 3m HUBER+SUHNER SUCODLEX 100



M1:2,04 GHz, 72,51 dBµV/m
M2:2,41 GHz, 66,87 dBµV/m
M3:2,69 GHz, 63,13 dBµV/m
M4:2,25 GHz, 63,15 dBµV/m

Figure 19: RF reference emitter noise measurement using 3m HUBER+SUHNER SUCODLEX 100 - Data points

The EMI emissions test results using the faulty High-loss EcoFlex 10 Plus coaxial cable are presented in Figures 20 and 21. The green limit line visible in Figure 20 is a pass limit for a certain emission test class. Using the faulty cable, this measurement is virtually a pass. The low-loss cable results in Figure 20 cross the limit at around 2 GHz and 2.5 GHz. The high-loss cable barely crosses the limit at around 2 GHz by 1.4 dBuV/m, and around 2.5 GHz it's well below the limit. These results highlight the reason cable loss measurements are necessary in any EMC laboratory. Unknowingly using a healthy-looking cable that has internal damage can cause highly inaccurate measurement results. The fault in this cable is not easily noticed without the cable loss measurement done in Section 5.

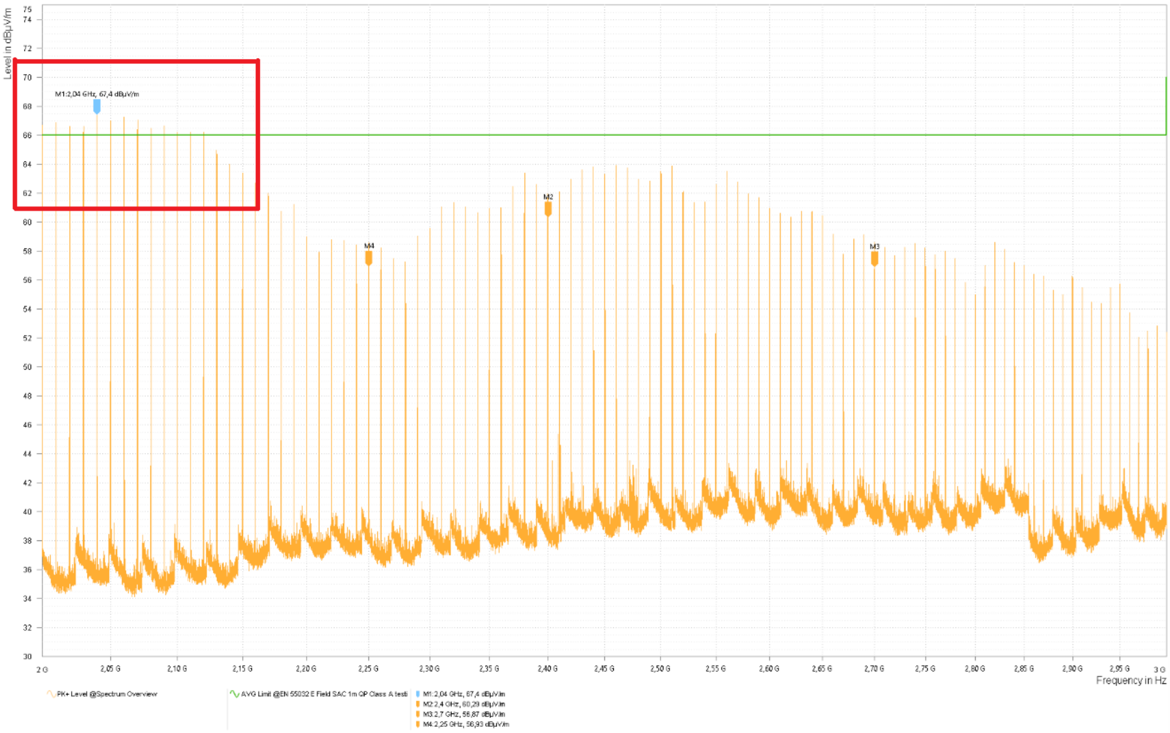
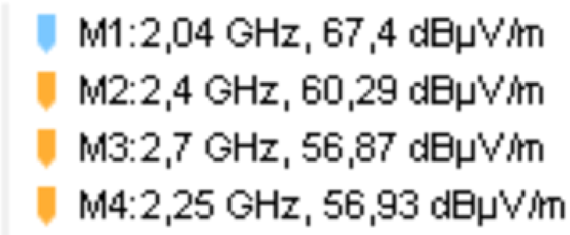


Figure 20: RF reference emitter noise measurement using 3 m EcoFlex 10 Plus



M1:2,04 GHz, 67,4 dBµV/m
M2:2,4 GHz, 60,29 dBµV/m
M3:2,7 GHz, 56,87 dBµV/m
M4:2,25 GHz, 56,93 dBµV/m

Figure 21: 3m EcoFlex 10 Plus and 3m HUBER+SUHNER SUCODLEX 100 data point comparison

7 Cable Loss compensation

Test results can automatically be compensated for cable attenuation by the measurement software. This requires specific frequency-dependent attenuation data, which was obtained using cable loss measurement steps in Section 3.3.

Cable loss compensation can be demonstrated by using the same setup as presented in Figure 16. Before and after compensation results are presented in Figures 22 and 23. A singular coaxial cable with normal attenuation does not significantly affect the results with its relatively low losses. This can be seen when comparing Figures 22 and 23; compensating a single cable does not change much. However, when a system has multiple cables, that's when cable loss compensation becomes more relevant.

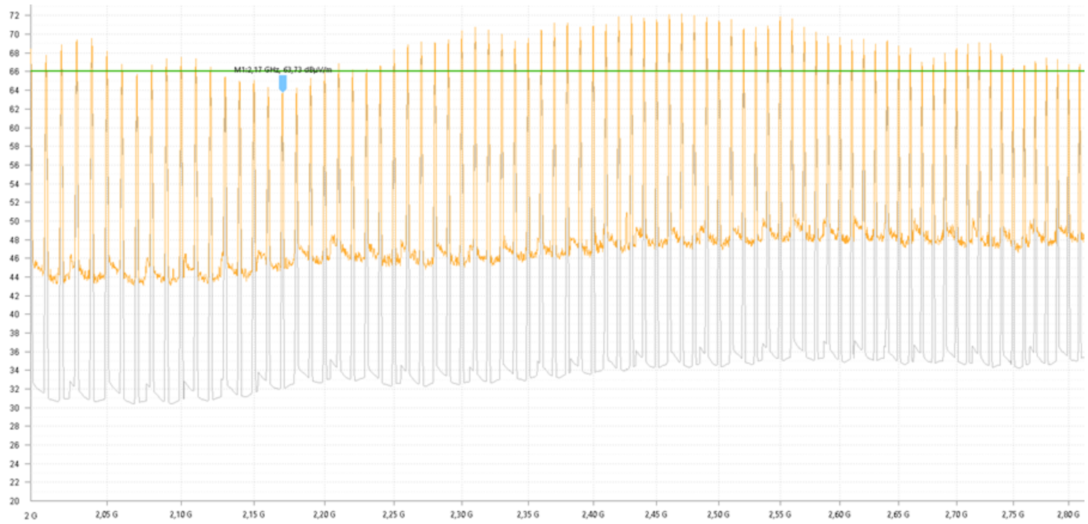


Figure 22: Example measurement results before cable loss compensation

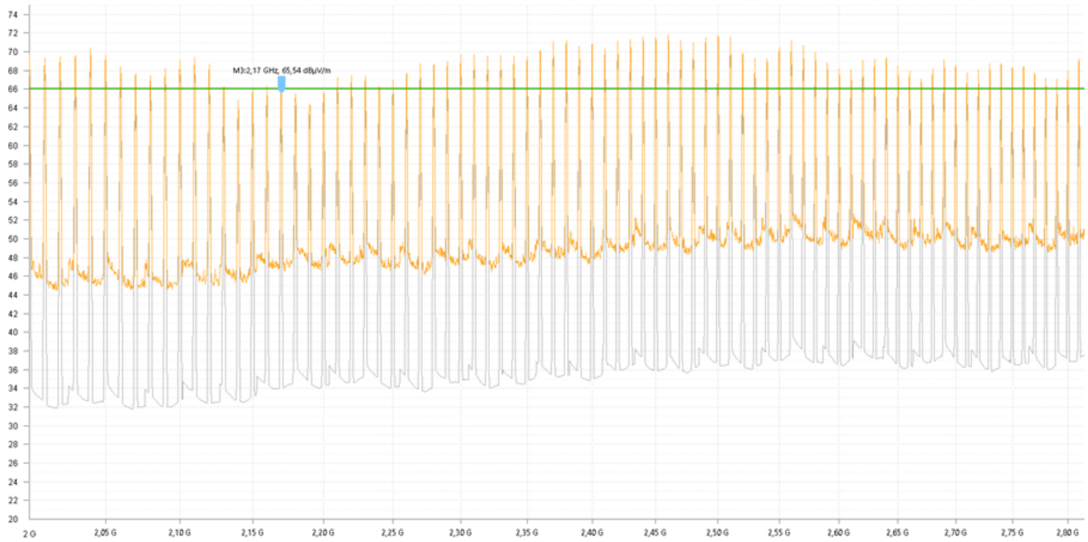


Figure 23: Example measurement results after cable loss compensation

8 Conclusion

The cable loss measurements showed mostly expected results. All except one of the tested cables had losses close to those provided in the datasheets. One coaxial cable gave readings of abnormally high cable losses and was deemed faulty. This faulty cable highlights the importance of periodically verifying that the cables used in EMC testing have appropriate losses. Since the faulty coaxial cable had no external signs of damage, test personnel using the cable can have no idea that the cable they are using is drastically affecting the measurement results. This can be especially true from an R&D testing standpoint since the personnel conducting the test might have no idea what kind of results to expect. This means false results might be accepted as valid, without considering faulty cables.

Return loss and VSWR measurements on the emission antenna system done in this paper returned expected results. Results were at an acceptable level with all tested antenna configurations. The measurements confirm that the impedance matching across the system is suitable for EMC testing applications. This result was expected since all of the components in the antenna system, except the coaxial cables, are calibrated separately by an accredited party.

All of the measurements done in this document are easily replicated in an EMC laboratory. The measurements not only enhance the accuracy of laboratory testing capabilities but also provide more certainty in the results. These tests can be done by the laboratory test personnel and do not require expensive equipment. After familiarising with the S331P, the measurements did not require extensive amounts of time, meaning test personnel can do these verification measurements whenever there is extra time, which means no downtime is required. At the bare minimum, periodical cable loss measurements of coaxial cables used in testing should be done in every EMC laboratory.

Summary

All objectives set were achieved successfully:

1. Coaxial cable attenuation was accurately measured as a function of frequency, confirming proper cable performance and identifying one faulty cable. [Section 5]
2. The measured loss data enabled improved accuracy in future tests by allowing compensation for cable attenuation. [Section 8]
3. Return loss and VSWR measurements confirmed proper impedance matching and validated the functionality of the antenna systems. [Section 4]

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