User's Guide for Kirkby Microwave 85033 SMA calibration kit.

Version 1.1 3^{th} July 2024.

Contents

1 Introduction

This document describes the Kirkby Microwave 85033 SMA calibration kit, which is available in versions for 7, 8, 9, 10, 11, 12 and 18 GHz. The kit is designed for Short Open Load Thru (SOLT) calibration, which is the most common type of calibration used at the frequencies of the kit. This is called TOSM (Thru Open Short Match) by Rohde &Schwarz. Each kit is supplied with individually measured data on each calibration standard, and a set of coefficients which are specific to that kit.

Note that the use of a 8 mm (0.315") torque spanner with a torque of 0.49 N m (4 lb inch) is **essential** when using the calibration kit. Finger tight is not sufficiently tight for reproducible results, and higher values of torque, which can be produced with a spanner, will prematurely wear the components. The torque spanner is sold as option 004, and there is space in the foam insert for the torque spanner.

The short and open calibration standards, as well as options 022 and 023 are made by combining various SMA parts. You should not attempt to disassemble the pieces. The pieces are tightened and secured with Locktite, so they will not come loose in normal use.

Note that the photographs in this document are not all of the one calibration kit. As such, serial numbers of parts shown here will not match the parts in the calibration kit.

2 Specifications

- **Function:** Calibration and verification kit.
- **Connector type:** SMA, which is suitable for calibration of SMA, 3.5 mm and 2.92 mm test ports.
- **Calibration types supported:** Short Open Load Thru (SOLT), which is also known as Thru Open Short Match (TOSM).
- **Frequency range:** DC to 7, 8, 9, 10, 11, 12 or 18 GHz.
- **Mechanical pin depth of the devices:** 0.000" to -0.010" (0 to -0.25 mm). Typically the pin depths are in the range 0.000" to -0.0025" (0.00 mm to -0.06 mm).
- **Phase error on opens:** The difference between the phase predicted by the mathematical model of the opens and the actual phase of the opens is ¡ 3°
- **Phase error on shorts:** The difference between the phase predicted by the mathematical model of the shorts and the actual phase of the shorts is ¡ 3°
- **Return loss of loads:** $\geq$ 32 dB.
- **Size:** 251 x 142 x 67 mm.
- **Weight:** Less than 1 kg. The exact weight depends upon the options chosen.
- **Colour of case:** Black is standard. Yellow can be supplied on request.
- **Format of coefficients data:** Data is supplied on a nano-sized USB stick of at least 16 GB is size. There are both human readable text files, and files readable by some VNAs.

3 Options

The following options are available for the kit and are not supplied as standard.

If options 001, 002, 003A, 003B, 003C or 003D are ordered, then the optional parts are stored in vials.

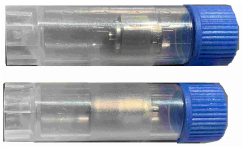

Figure 1: Photograph showing the vials used to store many of the options with small parts. The kit has space for 5 vials.

- **Option 001**. The Reverse Polarity SMA connector (RP. SMA) is very common on WiFi devices, such as routers, WiFi amplifiers, access points, antennas etc. Option 001 adds two reverse polarity SMA adapters, giving both male and female in reverse polarity. These have a measured electrical delay so their effect can be compensated for by port extensions, moving the reference plane, or whatever else your VNA calls such a procedure.

Figure 2: Photograph showing the two RP.SMA to SMA adapters. Photographs of each end of the two devices are shown.

- **Option 002.** This option provides a male SMA to male U.FL adapter, plus a female SMA to female U.FL adapter. The U.FL connector is regularly used internally in devices such as laptop computers, WiFi routers, and anywhere else where a small connector is needed to connect an item to a printed circuit board.

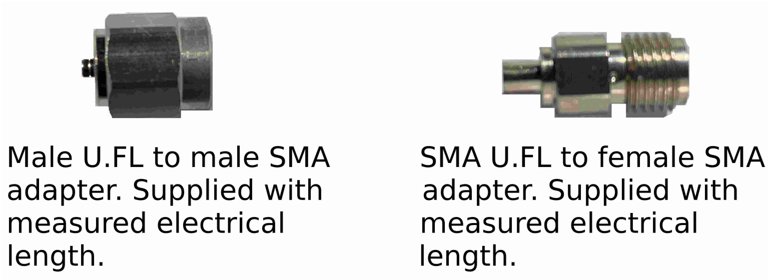

Figure 3: Photograph showing the two U.FL to SMA adapters. The upper frequency limit of the U.FL connector is 6 GHz. Normally U.FL connectors are designed for 20 matings, and mate very tightly requiring a tool to remove them. The adapters supplied use a low retention force design, which is designed for 500 matings.

- **Option 003A.** This option adds a pair of SMA to MMCX adapters, with measured electrical delay. Both male and female MMCX adapters are provided.

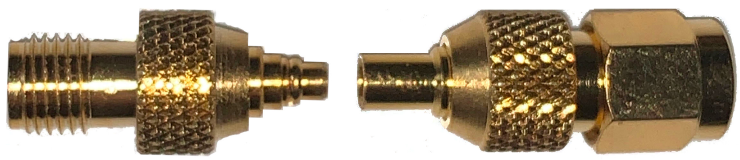

Figure 4: Photograph showing the two MMCX to SMA adapters included with kits with option 003A. The upper frequency limit of the adapters is 6 GHz.

- **Option 003B.** This option provides two SMA to SMB adapters. One has a male SMB connector and the other a female SMB connector. Both have a measured electrical delay.

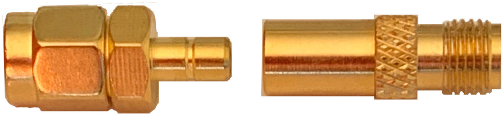

Figure 5: Photograph showing the two MMCX to SMA adapters included with kits with option 003B. The upper frequency limit of the adapters is 6 GHz.

- **Option 003C.** This option adds two SMC adapters, one with a male SMC connector the other a female SMC connector. The delay of both adapters is given.

- **Option 003D.** This option adds two SMA to MCX adapters, one with a male MCX connector and the other a female MCX connector. Both have a measured electrical delay.

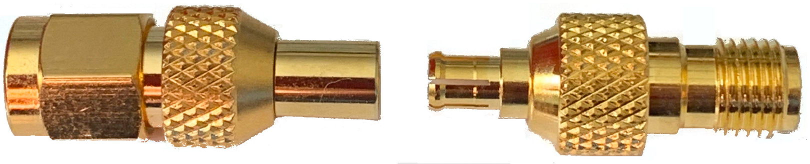

Figure 6: Photograph showing the two MCX to SMA adapters included with kits with option 003D. The upper frequency limit of the adapters is 6 GHz.

- **Option 003E.** Ordering this option means the kit will include 3 phase-matched SMA adapters. These can be used with the *Swap Equal Adapters* method of calibration, which is also known as when the S-parameters of a device under test (DUT) which is non-insertable - i.e. the DUT does not have a male and female connector. **This option is very useful with older VNAs such as the 8510C, 8719, 8720, 8722 or 8753 which do not support unknown thru calibration.** It is also useful with low-end modern instruments not supporting unknown thru. For a modern 2-port VNA with 4 receivers, supporting unknown thru calibration, this option is of no use, as unknown thru calibration is more convenient and more accurate.

Figure 7: Photograph showing the 3 phase matched adapters. Unlike the other optional adapters for use with the 85033 calibration kit, these adapters can be used to 27 GHz, but we only phase match these to the maximum frequency of the kit ordered, which is always 18 GHz or less.

- **Option 004.** This option adds a 0.49 N m (4 lb inch) torque spanner, which is **essential** for correct use of the calibration kit.

Figure 8: Photograph showing the option 004 torque spanner. A torque spanner with the correct torque is essential for accurate measurements

- **Option 006.** This option adds a floppy disk preloaded with the coefficients for an HP/Agilent 8510C VNA. This disk will look like that shown in figure 9.

Figure 9: Photograph showing a 3.5" floppy disk that can be used to load the coefficients into some early HP or Agilent VNAs.

- **Option 007.** This option adds a floppy disk preloaded with the coefficients for an HP/Agilent 8714 VNA. This disk will look similar to that shown in figure 9.
- **Option 009.** This option adds a floppy disk preloaded with the coefficients for an HP/Agilent 8719, 8720 and 8722 series of VNAs. This disk will look similar to that shown in figure 9.
- **Option 010.** This option adds a floppy disk preloaded with the coefficients for an HP/Agilent 8753 series of VNAs. This disk will look similar to that shown in figure 9.
- **Option 022.** This option adds an attenuator with two female connectors, which has properties measured by Kirkby Microwave using an Agilent 85052B calibration kit. It is quite a useful option as the use of two male test cables is common. This should only be used for comparisons with S12 and S21. The measurements of S11 and S22 can not be expected to be accurately reproduced as the return loss of the attenuator is high at low frequencies.

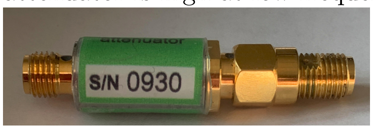

Figure 10: Photograph showing the option 022 attenuator with two female connectors. Port 1 is shown to the left, with the text up the correct way.

- **Option 023.** This option adds an attenuator with two female connectors, which has properties measured by Kirkby Microwave using an Agilent 85052B calibration kit. It is less useful than option 022, as it's rare to have a device under test with two male connectors. As with option 022, this should only be used for comparisons with S12 and S21.

Figure 11: Photograph showing the option 023 attenuator with two male connectors. Port 1 is shown to the left, with the text up the correct way.

4 Basics of network analyzer calibration

A detailed theory of network analyzer calibration can be found in the literature, particularly Keysight application notes, but the following is sufficient to understand the role of the calibration kit.

Like most test equipment, VNAs should be calibrated periodically by the manufacturer - typically once per year. The calibration performed by a calibration kit is performed much more frequently - often several times per day.

The simplest form of calibration is a one port calibration. Since vector measurements are made, and the cable lengths are often long compared to a wavelength, a calibration at the test port is not always that useful, although some VNAs are calibrated by the manufacturer at the test ports, especially if intended for portable use such as the Keysight FieldFox range. FieldFox range of Handheld Microwave and RF Analyzers.

When cables are connected to a VNA, there are 3 sources of error that would prevent accurate measurements without a calibration kit.

- **Directivity:** The coupler or bridge in the VNA is designed to measure the direction of propagation of a signal over a wide range of frequencies. Directional couplers that have high directivity are available, but only with a restricted frequency range. For example, Minicircuits make 3 couplers with a 40 dB directivity, but the highest frequency model is limited to 1 GHz.
- **Source match:** For true scattering parameter measurements, there has to be no power reflected at the other test ports. But the internal parts of the VNA do not present perfect 50 Ω loads, and even if they did, cables do not.
- **Reflection tracking:** This is the frequency response of the reflected signal from the device under test to the receiver in the VNA. The loss of the cables rises with frequency.

This gives 3 sources of error. These errors can be largely eliminated by measuring the properties of 3 devices of known properties and solving 3 simultaneous equations. Within reason it does not matter what 3 devices are measured, as long as their properties are known, and no two of the standards present the same impedance at the same frequency. However, if the impedance of two of the devices are very similar at some frequency, then noise on the measurements will mean the calibration will not be very good. Therefore, the following leads to an ideal set of calibration standards.

1. A perfectly matched device, which reflects 0% of the incident power.
2. A device which reflects 100% of the incident power. This is as different as possible to item 1.
3. Another standard, also reflecting 100% of the incident power, but being as different as possible to item 2. This means that the reflection is 180°out of phase with the item 2.

A good load is very similar to item #1. Two standards which exhibit the properties of 2 and 3 are shown as green and white lines in figure 28. The two devices should really be called offset-open and offset-short, as one is an open circuit, and the other a short circuit, but both offset some distance from the reference plane.

From the above description, it should be apparent that the software in the VNA needs to know the characteristics of the calibration standards. The more accurately they are known, the more accurate the calibration can be.

Each standard has been individually measured, and the Touchstone files of the short, open and load are on a nano sized USB stick included with the kit. The coefficients of the calibration standards, which are obtained using non-linear optimisation, and reproduced in this document.

The format of data used by different Vector Network Analyzers (VNAs) does depend to some extent on the model and manufacturer.

Data is provided in different formats. The vast majority of VNAs will be able to read the Agilent/Keysight format, consisting of an offset delay in ps and 3^{rd} order polynomial fits of the inductance and capacitance of the standards. Feel free to contact us if you are unsure of what is the most suitable format, or if required in a different format.

There are some human readable text files on the USB stick containing coefficients. These are not as accurate as those in the PDF document - in particular, the data on the shorts in the text files do not contain any inductance parameters. This PDF document is the best source of data.

5 VNAs supporting reading of Touchstone files for calibration standards

A minority of vector network analysers can read the Touchstone file of the calibration standard. If your model of VNA supports this, we recommend that the Touchstone files are used. The Touchstone files are on the USB stick.

6 Correct use of the torque spanner

The use of the correct torque spanner, which is available as option 004 if the user does not have one, is essential.

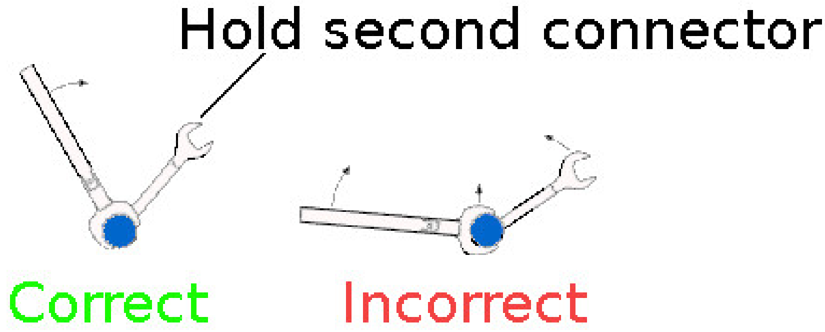

Figure 12: This shows how a torque spanner should be properly used. As one piece is tightened, the other pieces must be held so it does not rotate using a second spanner. The torque spanner and the other spanner should always be within 90°of each other.

Figure 13: This shows where the force should be applied to the torque spanner. If the torque spanner is gripped tightly in one hand, it is possible to get a higher but undefined torque.

7 Open Calibration Standards

Typically the open calibration standards are modelled as a length of transmission line terminated in a capacitor, which is the fringing capacitance. The fringing capacitance is frequency dependant. The capacitance C is given by the following 3$^{\text{rd}}$ order polynomial

$$C(f) = C0 \times 10^{-15} + C1 \times 10^{-27} f + C2 \times 10^{-36} f^2 + C3 \times 10^{-45} f^3$$

where C is in farads and f in Hz. The transmission line has some length, and so delay. The values of $C0, C1, C2$ and $C3$ as well as the delay are computed from measurements made after the kit is manufacturer. These are individually measured for each calibration kit, and are given on the calibration certificate, which is supplied with the calibration kit.

7.1 Female Open

Figure 14: Photograph showing the two types of female open used in the 85033 calibration kit. The 12 and 18 GHz models use those on the left. Lower frequency kits sometimes use the female open on the right. Do not be surprised by some small differences - sometimes the open section is all gold plated.

7.2 Male open

Figure 15: Photograph showing the two types of male open used in the 85033 calibration kit. The 12 and 18 GHz models use those on the left. Lower frequency kits usually (but not always) use the male open on the right.

8 Short calibration standards

As stated in the introduction, many VNAs o not allow any data other than the length or delay of a short. But when they do, the short calibration standards are modelled as a length of transmission line terminated in an inductor. This inductance is frequency dependant. The inductance L is given by the following 3$^{\text{rd}}$ order polynomial

$$L(f) = \texttt{L0} \times 10^{-12} + \texttt{L1} \times 10^{-24} f + \texttt{L2} \times 10^{-33} f^2 + \texttt{L3} \times 10^{-42} f^3$$

where L is in henrys and f in Hz. The transmission line has some length, and so delay.

8.1 Female short calibration standards

Figure 16: Photograph showing the two types of female short used in the 85033 calibration kit. The 12 and 18 GHz models use those on the left. Lower frequency kits usually (but not always) use the male short on the right.

On most modern VNAs, the female shorts are designated as `SHORT -F-`. However, Keysight, which was formally Agilent, which was formally HP, have used a different convention on older instruments, which included

- The 8510C and 8712, 8714, 8719, 8720, 8722 and 8753 series vector network analyzers.
- Some, but not all ENA series instruments.

On the older instruments, these would be designated as `SHORT (M)`, to indicate the short calibration standard was used with a male test port. Notice the parentheses rather than hyphens.

8.2 Male shorts

Figure 17: Photograph showing the two types of male short used in the 85033 calibration kit. The 12 and 18 GHz models use those on the left. Lower frequency kits usually (but not always) use the male short on the right.

9 Load calibration standards

Purchasing loads with a **guaranteed** return loss demanded by a VNA calibration kit is very expensive. A single load purchased from Keysight will cost as much as Kirkby Microwave charge for many calibration kits.

Kirkby Microwave purchase a large number of different SMA loads from companies such as Minicircuits, Rosenberger, Telegarner, Huber and Suhner etc. The performance of each is measured, and put into 1 of 4 categories

1. Loads with a return loss of less than 32 dB at 7 GHz. These are unsuitable for VNA calibration kits, but we use them for other purposes. **Around 70% of loads fall into this category, which is why replacing one of our loads with the same part number from the same manufacturer will almost certainly result in a load unsuitable for a VNA calibration kit at 7 GHz.**

2. The load is suitable for an 18 GHz VNA calibration kit. These are **very** rare, and any load found suitable for an 18 GHz calibration is kept for that purpose. Only around 5% of loads meet this requirement.
3. The load is suitable for a 12 GHz VNA calibration kit, but not suitable for an 18 GHz kit. These are rare, with around 10% of loads falling into this category.
4. Loads suitable for calibration kits between 7 and 11 GHz. Around 15% of loads fit into this category.

All loads have a high return loss, so defining the load to be a pure 50 Ω will work well. However, for a VNAs supporting entry of Touchstone files for the loads, the data on the USB stick will give improved performance.

9.1 Female load

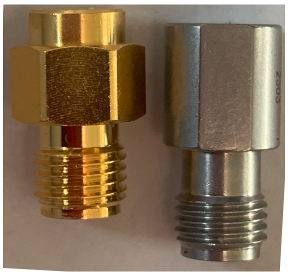

Figure 18: Photograph showing two of several types of female load used in the 85033 calibration kit. If the loads need to be replaced, then contact us, as all loads are specially selected for use in calibration kits.

9.2 Male load

Figure 19: Photograph showing two of several types of male load used in the 85033 calibration kit. Do not be tempted to replace the loads with a similar or identical looking device. Many loads of the same manufacturer and model number will have inferior performance. Each load is specially selected, and not all loads are suitable for calibration kits.

10 Thru calibration standards

If a full 2-port calibration is needed, and one test lead is male, and the other female, then no thru standard is required to perform the calibration.
However, having two test leads of the same gender is quite common - usually two male connectors. In this case a thru has to be added to allow the calibration to be performed. If a modern VNA is used which supports unknown thru calibration (call UOSM by Rohde and Schwarz) then virtually any reciprocal thru (S12=S21) can be used. This is the most accurate way of performing a 2-port calibration.
However, if unknown thru / UOSM calibration is not supported, then a thru needs to be added, and the delay taken into account. The data below gives the measured delay of the thru sections. These will need to be entered into the calibration kit definition in the VNA. The delay will be zero.

10.1 Female-female thru

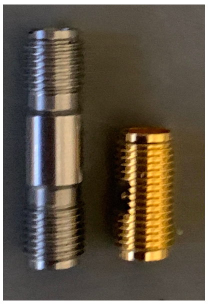

Figure 20: Photograph showing the two types of female-female thru used in the calibration kit. The delay of these is measured. These are not phase matched to the male-male thru unless option 003E is ordered, which also adds a male-female thru.
`Delay of female-female thru: 78.402002 ps`

10.2 Male-male thru

Figure 21: Photograph showing two of the types of male-male thru used in the calibration kit. The device in your kit may look slightly different. The delay of these is individually measured. These are not phase matched to the male-male thru unless option 003E is ordered, which also adds a male-female thru.
`Delay of male-male thru: 75.001999 ps`

11 Reference attenuators

Each kit is supplied with at least one attenuator which can be used to compare measurements made by Kirkby Microwave to that made by a customer. Any major differences would be cause for concern. The attenuators supplied are listed below. In each case port 1 is to the left when the text is up the correct way.

- Attenuator with one male connector and one female connector. This is included with every kit.

  

  Figure 22: Photograph showing the standard reference attenuator included with every 85033 calibration kit. The serial number should match that of the calibration kit.
- Attenuator with two female connectors. **This is only supplied with kits ordered with option 022.** This is a very useful addition to a kit, as frequently people use two cables, each with a male connector, to connect to DUTs which most frequently have female connectors.

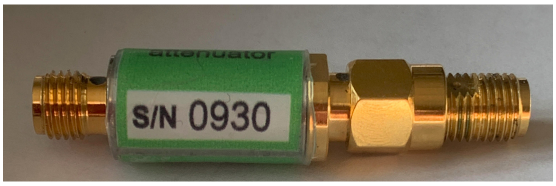

Figure 23: Photograph showing the optional reference attenuator with two female connectors included with kits with option 022. The serial number will be different to that of the calibration kit.

- Attenuator with two male connectors. **This is only supplied with kits ordered with option 023.** This is a less useful addition to a kit than option 022, as it is rare to have a device under test (DUT) with two male connectors.

Figure 24: Photograph showing the optional reference attenuator with two male connectors, included in kits with option 023. The serial number will be different to that of the calibration kit.

12 USB stick

Figure 25: Photograph showing the 32 GB USB stick. This has data on the calibration kit, as well as some other material which users may find useful.

Each kit is provided with a nano-sized USB stick. The following directories are on the USB stick. Note some of them doe not contain anything specific to the kit, but are provided as they may be of use to the reader.

- `Antenna-related-material` As the name suggests, this is about antennas. This is **not** specific to the calibration kit.
- `data-on-RP.SMA-and-U.FL-adapters-if-included-in-kit`. This had data on the option 001 (RP. SMA) and option 002 (U.FL) devices in the kit.
- Human-readable-coefficients. This has data files in a human readable format. **Note that the software used to generate this is not as good as that used to generate the data in the PDF document with the name Manual-for-85033-SNxxxx.pdf.**
- `Measured_data_of_option_022_female-female_attenuator` This directory will not have any measured data unless option 022 was ordered.
- `Measured_data_of_option_023_male-male_attenuator` This directory will not have any measured data unless option 023 was ordered.

13 Verification of the correct calibration

It is imperative that the VNA is set up correctly to use the calibration kit. The procedure for doing this will depend upon the VNA, but in general will require that a user-defined calibration kit is used. The parameters of the calibration standards will have to be defined. The properties of the calibration standards are given above. The following is a suggested technique to verify the calibration.

13.1 Measure the calibration standards

Measuring the calibration standards will not tell you anything about the accuracy of the calibration, but it will highlight if there are obvious errors in the entry of the coefficients. A directory on the USB stick will have 4 files showing the measured phase of both opens and both shorts.

Do not be alarmed that the phase is the same at multiple frequencies. The mathematical model of the calibration standards takes that into account. Do not be surprised if the graphs you receive look quite different, because different kits are constructed different ways, and result in different phases at the same frequency.

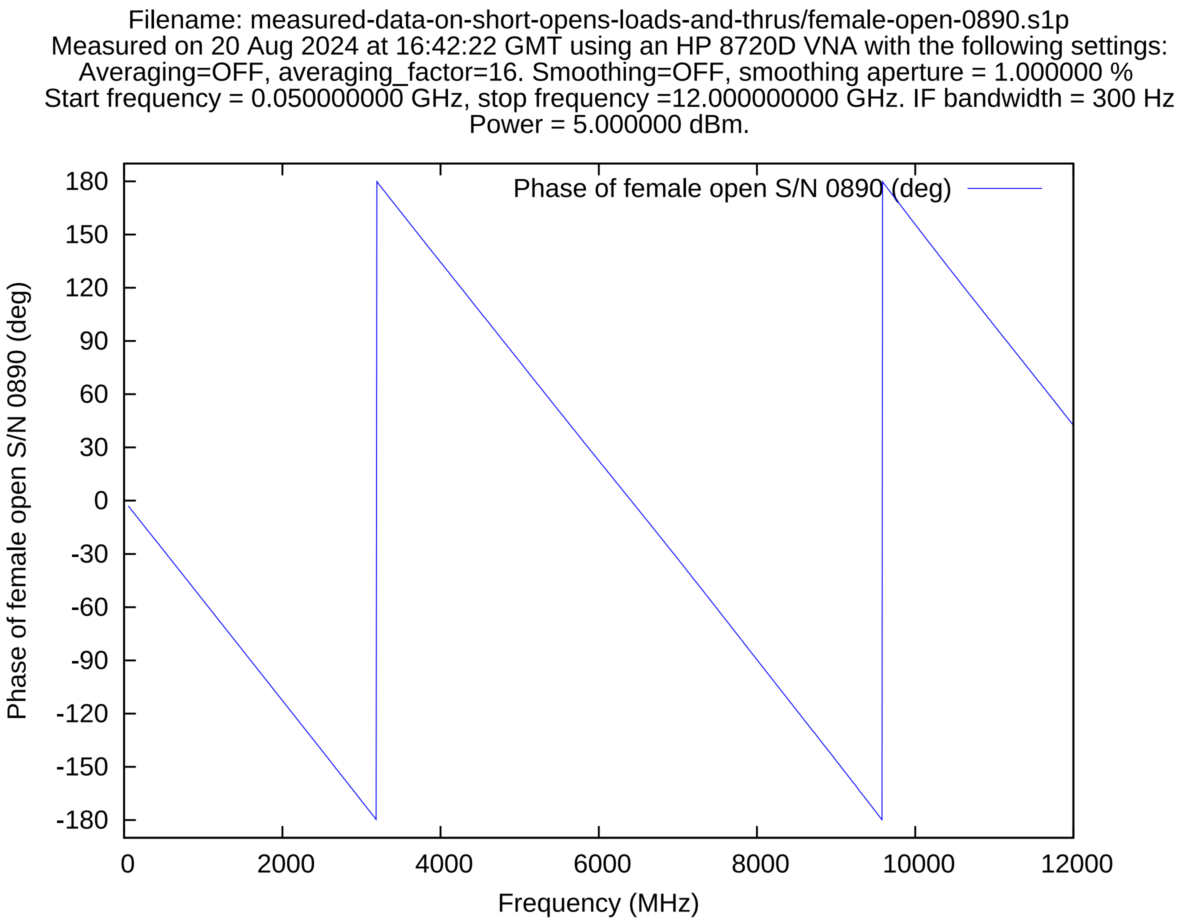

Figure 26: A typical plot of the phase of the female open calibration standard, which will be close to 0°at the lowest frequency.

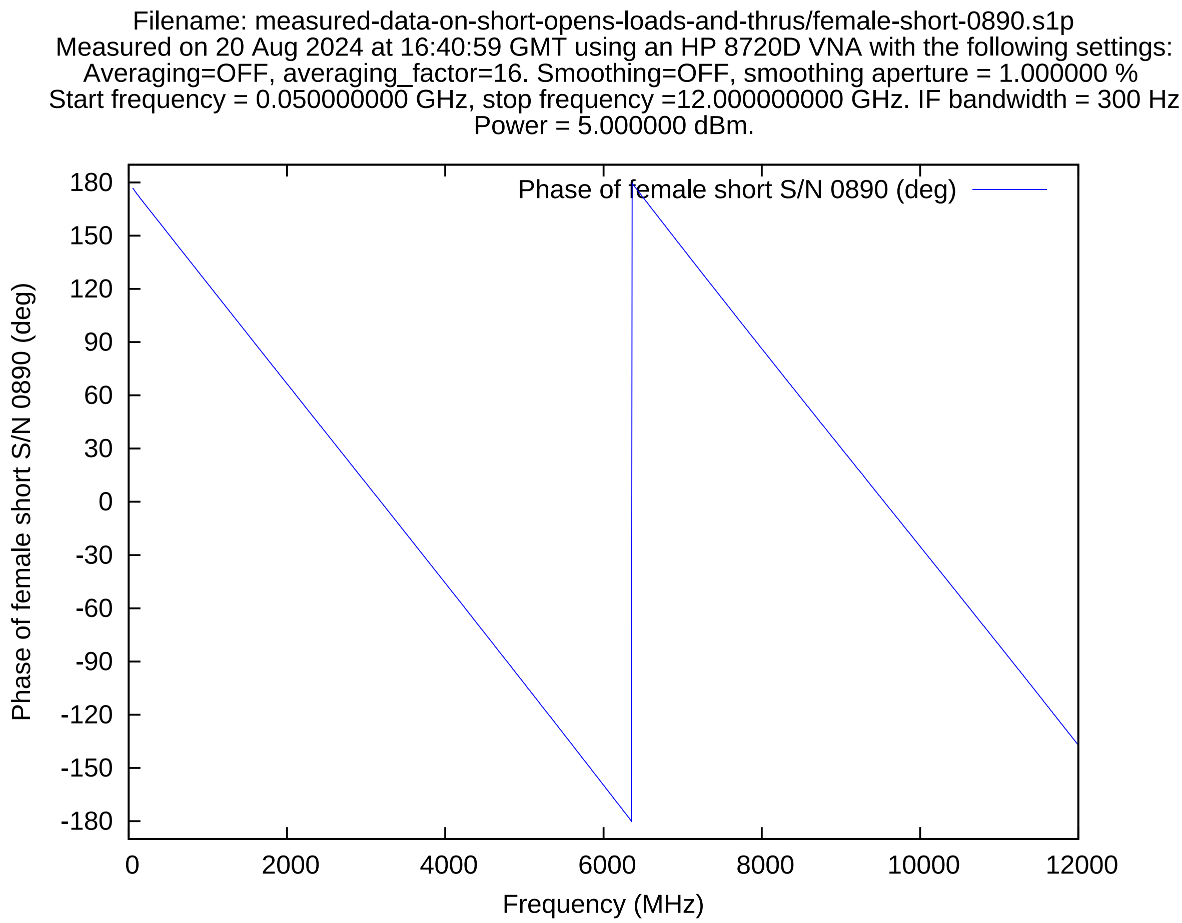

Figure 27: A typical plot of the phase of the female short, which will be close to 180°at the lowest frequency. The difference in phase between the open and short should be within 20°of 180°at all frequencies. If you can save a display of the open, and show the short at the same time, using a reference of 0°and a scale of 45°/division, you should see something like figure 28, with the two traces always around 4 divisions (180°) away from each other.

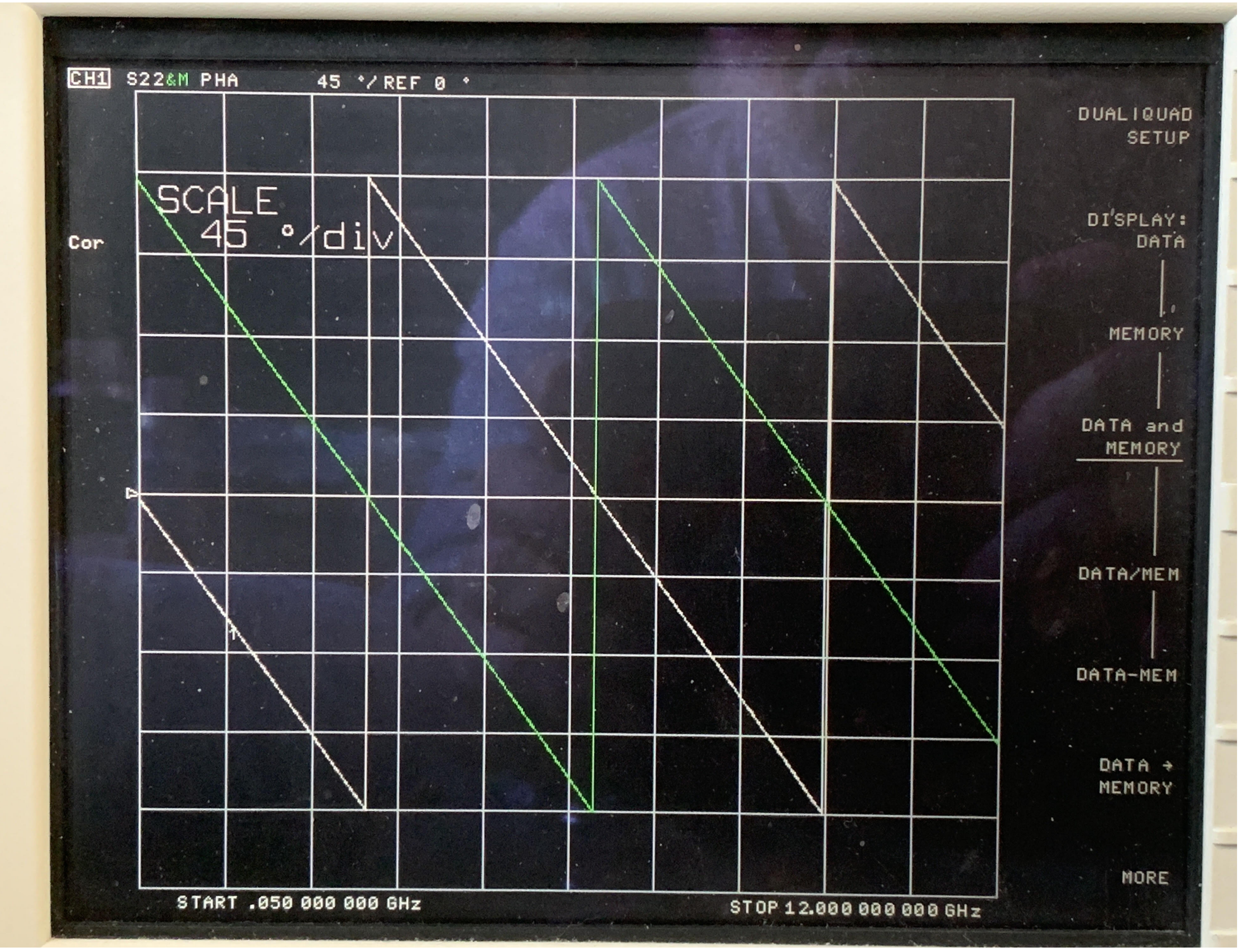

Figure 28: A display on a vector network analyzer, with the phase of the female short shown in green and the open in white. Since each division is 45°, a difference of 4 divisions is 180°, which is the ideal phase difference between the open and short, although any phase difference greater than around 20°will allow a calibration, but small phase differences lead to less stable calibration, with more noise.
Note that in the lower frequency kits, the phase of the males will be significantly different to the females. This is not a problem, as the mathematical model of the calibration standards takes this into account.
It's important to note that just remeasuring the calibration standards does not mean that measurements are being made correctly. However, if the measurements of the calibration standards is similar to that in the Touchstone files provided, then it would tend to indicate the kit has been set up correctly. Further tests are required to increase confidence in the results.

13.2 Measure S21 and S12 of the standard male-female attenuator

All calibration kits are supplied with an attenuator with a male connector and a female connector as shown in figure 22. The data is provided as a PDF with the filenames `attenuator-xxxx-S21.pdf` and `attenuator-xxxx-S12.pdf`, where `xxxx` is the serial number of the calibration kit. The data can be plotted from the Touchstone file `attenuator-xxxx.s2p`. The results will look something like those shown in figure 29

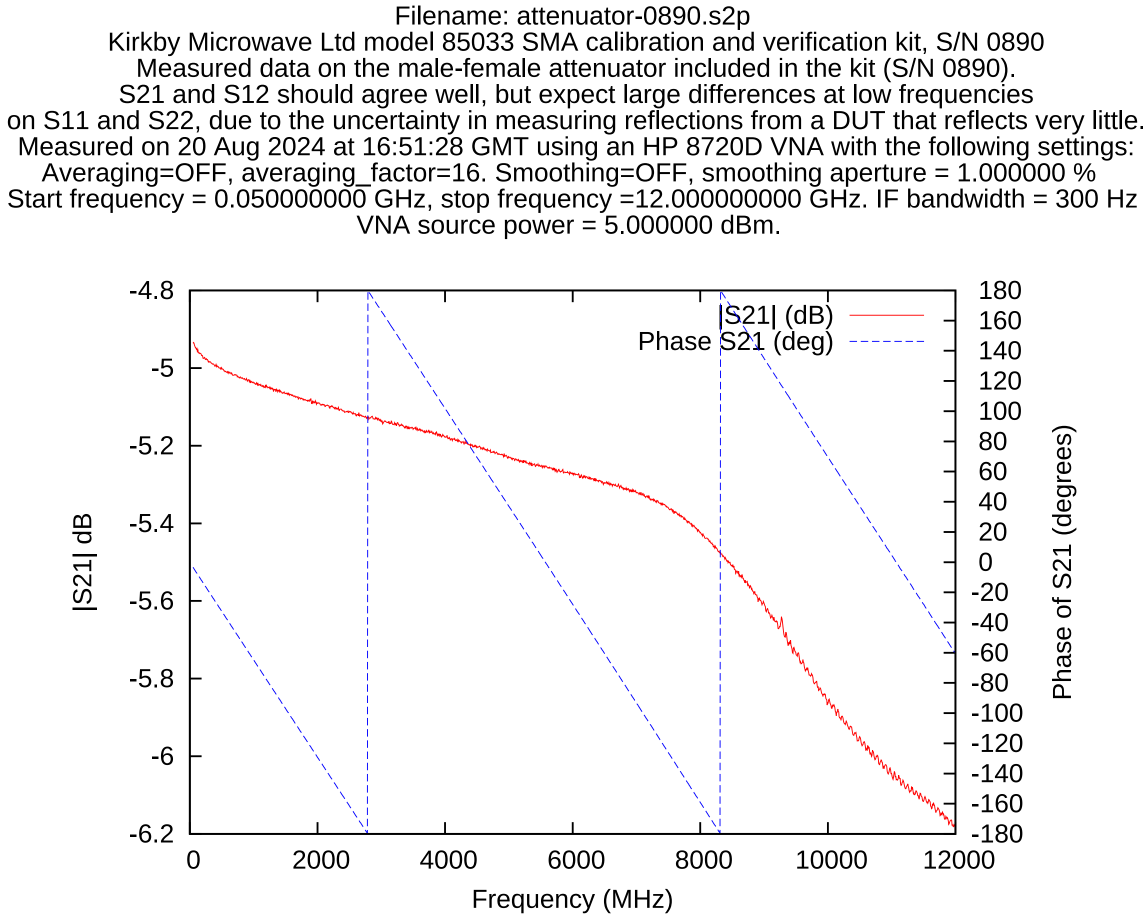

Figure 29: Typical results of measurement of the male-female attenuator. Comparisons with S11 and S22 are not likely to be useful, especially at lower frequencies where the return loss of the attenuator is so high.

13.3 Using the standard attenuator for verification of reflection coefficient

As stated above, S11 and S22 data on the attenuator cannot be used as the return loss of the attenuator is high, and so the measurement uncertainty high. However, the attenuator can be configured to have a return loss of around 12 dB by measuring at the male port, and leaving the female port unterminated as shown in figure 30.

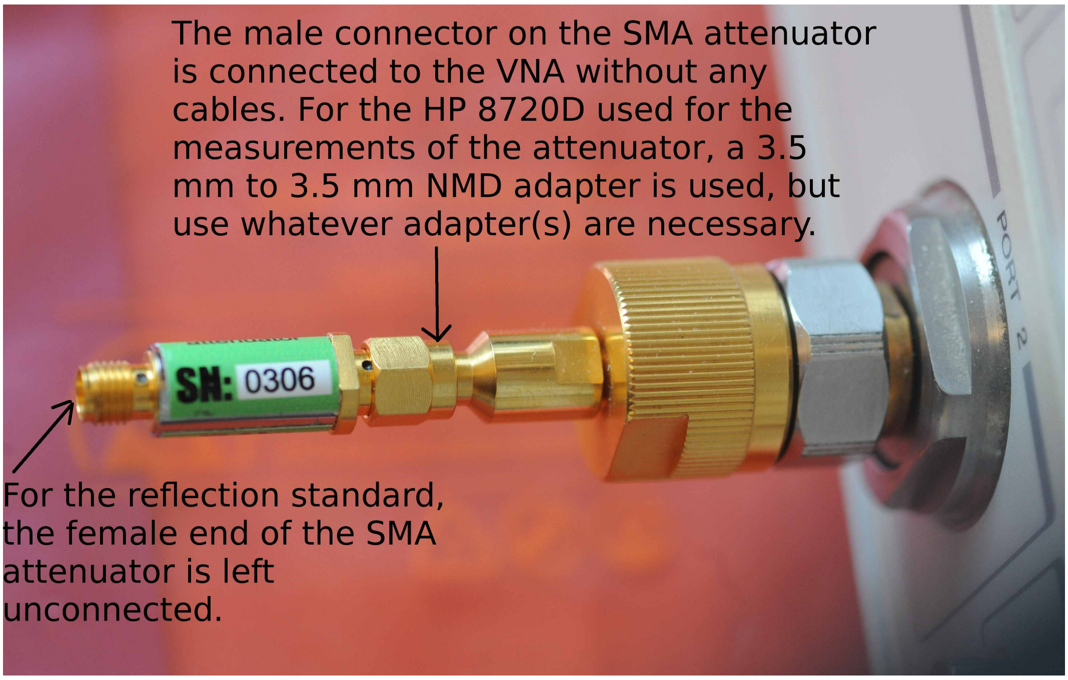

Figure 30: Using the attenuator as a reflection standard. Data on this is given in the Touchstone file `attenuator-xxxx-reflection-coefficient-at-male-port-with-female-port-unterminated.s1p` and plotted in the file
`attenuator-xxxx-reflection-coefficient-at-male-port-with-female-port-unterminated.pdf`
A typical plot is shown in figure 31.

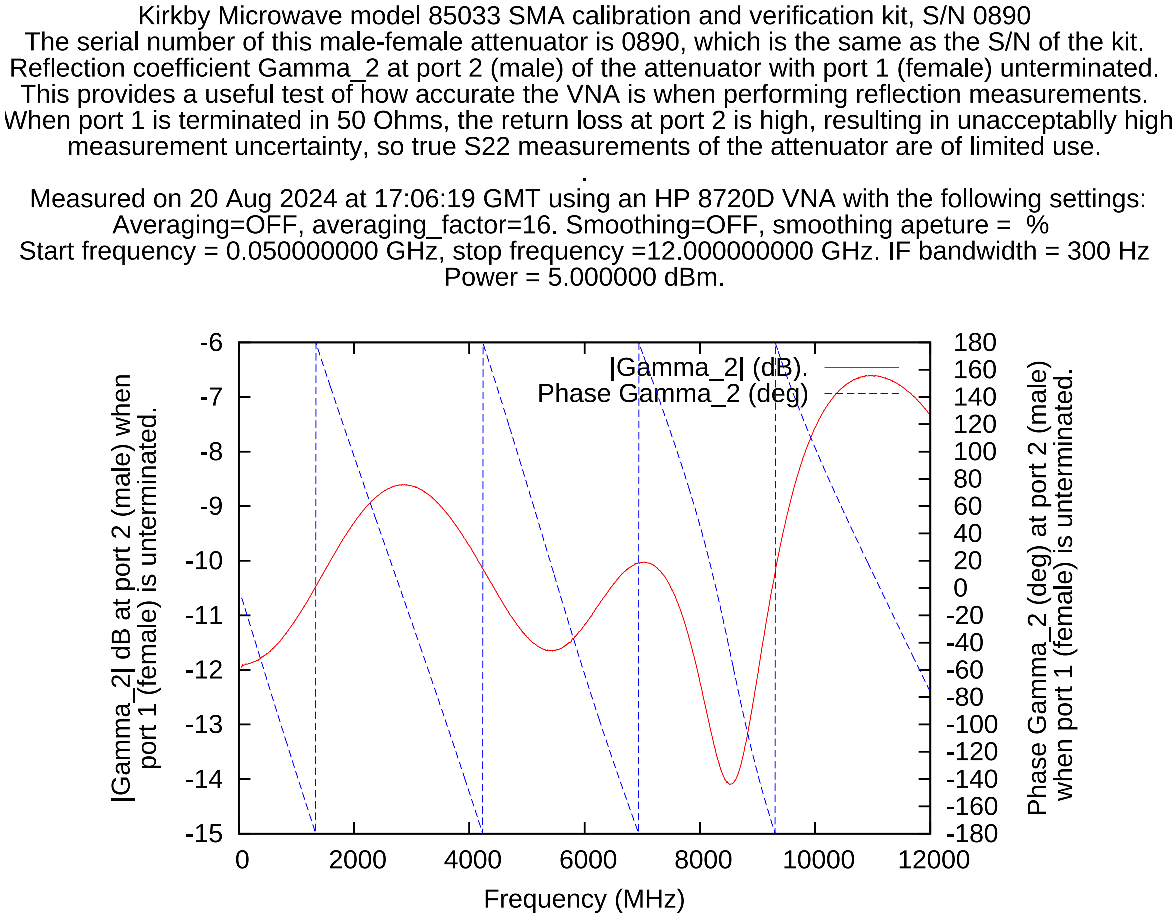

Figure 31: Typical results of a reflection measurement at the male port of the male-female attenuator. Results are also shown with the male port unterminated, but these are less reliable, especially at higher frequencies, as the nut on the SMA plug changes its proximity to the male centre conductor.

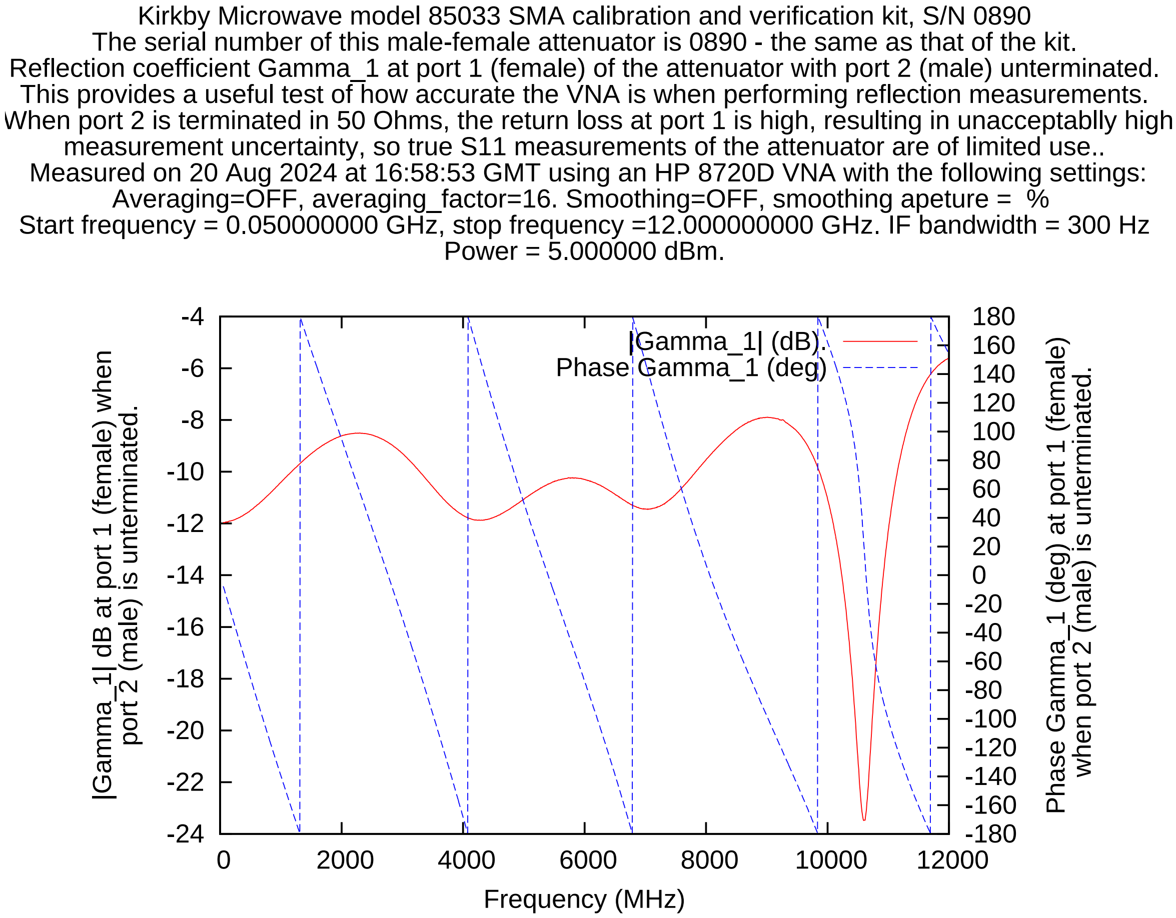

Figure 32: Typical results of a reflection measurement at the female port of the male-female attenuator, with the male port unterminated. Whilst these can be useful at low frequencies the movement of the nut on the male end of the connector means this is an unstable combination

13.4 Measure option 022 and/or option 023 attenuator

If option 022 or 023 are ordered, then these should be measured too. Since these attenuators are non-insertable, more care is needed in the calibration of the VNA with these.

14 Using the option 003E/003F phase matched adapter set

This section is to be written. Option 003E was not purchased with calibration kit S/N 0890, so it is irrelevant.