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Calibrating a Vector Network Analyzer for Accurate Measurements in Radio-Frequency Propagation Channels

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Corresponding Author:	Chriss Hammerschmidt National Telecommunications and Information Administration Boulder, CO UNITED STATES
Corresponding Author's Institution:	National Telecommunications and Information Administration
Corresponding Author E-Mail:	chammerschmidt@ntia.gov
Order of Authors:	Chriss Hammerschmidt
	Robert T. Johnk
	Savio Tran
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1   **TITLE:**
2   Calibration of Vector Network Analyzer for Measurements in Radio Frequency Propagation
3   Channels
4
5   **AUTHORS AND AFFILIATIONS:**

6   Chriss A. Hammerschmidt[1], Robert T. Johnk[1], Savio Tran[1]
7
8   [1]National Telecommunications and Information Administration, Institute for
9   Telecommunication Sciences, Boulder, CO, USA
10
11   **Corresponding Author:**
12   Chriss A. Hammerschmidt   (chammerschmidt@ntia.gov)
13
14   **Email Addresses of Co-authors:**
15   Chriss A. Hammerschmidt   (chammerschmidt@ntia.gov)
16   Robert T. Johnk   (rjohnk@ntia.gov)
17   Savio Tran   (stran@ntia.gov)
18
19   **KEYWORDS:**
20   best practices, spectrum sharing, propagation modeling, channel sounder architecture,
21   telecommunications, interference
22

23   **SUMMARY:**
24   This protocol describes best practices for calibrating a vector network analyzer prior to use as
25   an accurate instrument, intended to measure components of a radio frequency propagation
26   measurement test system.
27
28   **ABSTRACT:**
29   In situ measurements of radio frequency (RF) spectrum activity provide insight into the physics
30   of radio frequency wave propagation and validate existing and new spectrum propagation
31   models. Both of these parameters are essential to supporting and preserving interference-free
32   spectrum sharing, as spectrum use continues to increase. It is vital that such propagation
33   measurements are accurate, reproducible, and free of artifacts and bias. Characterizing the
34   gains and losses of components used in these measurements is vital to their accuracy. A vector
35   network analyzer (VNA) is a well-established, highly accurate, and versatile piece of equipment
36   that measures both magnitude and phase of signals, if properly calibrated. This article details
37   the best practices for calibrating a VNA. Once calibrated, it can be used to accurately measure
38   components of a correctly configured propagation measurement (or channel sounding) system
39   or can be used as a measurement system itself.
40
41   **INTRODUCTION:**
42
43   The Institute for Telecommunication Sciences (ITS) is the research laboratory of the National
44   Telecommunications and Information Administration (NTIA), an agency of the U.S. Department

45 of Commerce. ITS has been active in radio propagation measurements since the 1950s.
46 Spectrum sharing, the new paradigm for federal and commercial spectrum users, requires that
47 two disparate systems share the same radio frequency spectrum at the same time. As spectrum
48 sharing scenarios increase, so does the need for accurate and reproducible radio propagation
49 measurements that provide a better understanding of the radio environment, which multiple
50 services must share. The goal of the described procedure is to ensure that any components
51 constituting such a system are well-characterized by an accurately configured VNA.
52
53 While demand for spectrum increases, it is not always possible to rapidly free spectrum that is
54 currently used by federal agencies for commercial purposes. For example, in the Advanced
55 Wireless Services (AWS)-3 band (1755–1780 MHz), spectrum sharing arrangements are being
56 developed between military services and commercial wireless carriers[1]. These arrangements
57 allow commercial wireless carriers to enter the AWS-3 band prior to completing the transition
58 of military services out of the band.
59
60 The Defense Spectrum Organization (DSO) has been tasked with managing the AWS-3
61 transition. A key part of the transition involves developing new propagation models to evaluate
62 the potential for RF interference between military and commercial wireless systems that share
63 the band. The DSO has tasked ITS and others with performing a series of channel sounding
64 measurements to build new models that better calculate the impact of foliage and man-made
65 structures in the environment (collectively known as clutter). Improved propagation modeling
66 that considers clutter will lead to fewer restrictions on commercial transmitters in the vicinity of
67 military systems.
68
69 In situ measurements of RF spectrum activity provide insight into the physics of RF wave
70 propagation and validate existing and new radio propagation models. Both of these
71 components are essential to supporting and preserving interference-free spectrum sharing.
72 Channel sounding techniques, in which a known test signal is transmitted from a specific
73 location to either a mobile or stationary receiver, provide data that estimates radio channel
74 characteristics in different environments. The data are used to develop and improve models
75 that more accurately predict propagation losses or attenuation of the signal. These losses may
76 be due to blocking and reflection by buildings and other obstacles (i.e., trees or terrain in urban
77 canyons). These obstacles produce multiple, slightly variant, propagation paths resulting in
78 signal loss or attenuation between the transmitting and receiving antenna.
79
80 ITS measurement techniques produce accurate, repeatable, and unbiased results. The DSO has
81 encouraged ITS to share its institutional knowledge with the wider technical community. This
82 knowledge includes how to optimally measure and process RF propagation data. The recently
83 published NTIA Technical Memorandum TM-19-535[2-5] describes a set of best practices for the
84 preparation and verification of radio propagation measurement systems. As part of these best
85 practices, a VNA is used to accurately measure the component losses or gains of a
86 measurement system. The gains and losses are then used to calculate the signal attenuation
87 between two antennas.
88

89   The protocol presented here addresses the best practices for calibrating a VNA[5] prior to testing
90   in laboratory or field applications. These include warm-up time, selection of RF connector type,
91   making proper connections, and performance of appropriate calibration steps. Calibration
92   should be conducted in a controlled lab environment prior to data collection in the context of a
93   specific propagation measurement scenario. Additional considerations may be relevant to
94   specific propagation measurement environments, which are outside the scope of this protocol.
95
96   The VNA is used to measure device characteristics of components and sub-assemblies when
97   assembling other measurement systems. Power amplifiers, receivers, filters, low noise
98   amplifiers, mixers, cables, and antennas are all components that can be characterized by a VNA.
99   Prior to testing and/or calibrating a system, a list of all required components of the system is
100   prepared, and all system components are assembled. Each component of a system is measured
101   separately by inserting them between the VNA cables. This ensures that all components are
102   operating within the manufacturer's specifications. Once the components have been checked,
103   the system is assembled, and losses throughout the entire system are measured. This ensures
104   that reflections and transmissions between components are properly characterized.
105
106   A VNA measures scattering parameters (S-parameters), which are complex-valued quantities
107   with both magnitude and phase. An S-parameter is a ratioed measurement of either the 1)
108   reflected signal to the incident signal (reflection measurement) or 2) transmitted signal to the
109   incident signal (transmission measurement). For a two-port device, four S-parameters (S_{11}, S_{21},
110   S_{12}, and S_{22}) can be measured. The first subscript refers to the port where the signal is received,
111   and the second refers to the port where the signal is transmitted. Thus, S_{11} means the
112   transmitted signal originated at port 1 and was received at port 1. Additionally, S_{21} means that
113   the transmitted signal originated again at port 1 but is received at port 2. S_{11} measures the
114   amount of signal that is reflected by the device under test (DUT) at port 1 with reference to the
115   original signal that was incident at port 1. S_{21} measures the amount of signal that is transmitted
116   through the DUT and arrives at port 2 with reference to the incident signal at port 1. S_{11} is a
117   measure of the reflection coefficient of the DUT at port 1, and S_{21} is a measure of the
118   transmission coefficient of the DUT from port 1 to port 2.
119
120   A calibration of the VNA is required to remove the systematic errors from components up to
121   (and including) the measurement reference plane, which is typically at the end of the VNA
122   measurement cables. A calibration removes system errors by measuring "perfect" known
123   standards (open, shorts, loads, thru/line) and comparing it to the value that the VNA measures.
124   Through a series of error corrections, a corrected value for the DUT is displayed. There are
125   currently 12 error terms[6,7] that are characterized during calibration. For more information, refer
126   to original S-parameter measurements that were made on six-port network analyzers[8]
127   supported by classical microwave circuit theory[9,10].
128
129   The most common types of S-parameter reflection measurements are return loss, standing
130   wave ratio (SWR), reflection coefficient, and impedance matching. The most common types of
131   S-parameter transmission measurements are insertion loss, transmission coefficient, gain/loss,
132   group delay, phase or phase delay, and electrical delay. Transmission loss measurements are

133 emphasized in the described protocol.
134
135 Measurement of gains and losses of system components using a VNA is well-understood.
136 However, important steps are often skipped, such as cleaning connectors and using a proper
137 torque wrench. This protocol provides all necessary steps and explanations of why some are
138 particularly important. It will also serve as a prelude to a future article describing how to
139 perform RF propagation measurements, including the calculations of signal attenuation.
140
141 **PROTOCOL:**
142
143 **1. VNA set-up**
144
145 1.1. Gather all components of the propagation measurement system, including cables,
146 amplifiers, filters, DUTs (which can be subassemblies) and other components.
147
148 1.2. Turn on the VNA (**Figure 1**), and let it warm for at least 0.5 h to ensure that all internal
149 components of VNA are a stable operating temperature and that phase drift is minimized.
150
151 1.3. Press the **Preset** button.
152
153 1.4. Attach high quality, phase-stable cables to ports 1 and 2 of the VNA (**Figure 2**).
154
155 1.5. Tighten the connectors at the VNA ports with an 8 in.lbf. torque wrench. To properly torque
156 a connection, hold the end of the handle and gently push the handle without allowing the handle
157 to break all the way over.
158
159 1.6. Visually inspect all cables and connectors for obvious signs of wear such as nicks, dents,
160 and imperfect connector threads.
161
162 1.7. Check the manufacturer's specifications for valid measurement ranges for all cables,
163 connectors, and DUTs. These specifications can include temperature, humidity, frequency, and
164 power.
165
166 1.8. Clean connectors on all devices and cable ends. Use swabs specifically designed for
167 cleaning sensitive electronics and connectors. Using cables with dirty connectors can result in
168 damaging the conducting surfaces of cables and produce inaccurate measurements.
169
170 1.8.1. Dip a cotton swab into isopropyl alcohol.
171
172 1.8.2. Gently clean the center conductor (**Figure 3A**) using the moistened swab. Do not exert
173 too much force on the center conductor, as it is easily damaged.
174
175 1.8.3. Clean the outer conductor of each connector (**Figure 3B**). Clean the coupling nut threads.
176

177 1.8.4. Dry all cable and connector ends using clean compressed air (**Figure 3C**). If the
178 compressed air cools the connector, allow the connector to return to room temperature (RT)
179 before making and tightening all connections.
180
181 1.9. Align and make connections between VNA cables on ports 1 and 2 and the DUT. Tighten
182 with a 12 in.lbf. torque wrench for type N connections (**Figure 4**). Ensure that the cable ends are
183 properly aligned.
184
185 1.9.1. Begin spinning the connector on the DUT side onto the VNA cable threads. Proper
186 connections allow the nut to spin freely with little resistance. Resistance is a sign of cross-
187 threading. Misalignment can damage the connector or cause signal reflections and signal loss.
188 Do not overtighten connector, as this will damage the connector.
189
190 1.9.2. Arrange the cables of the VNA such that they move minimally during calibration.
191 Calibration cables are phase-stable and ideally not bent or moved during calibration.
192
193 1.10. Adjust VNA measurement parameters according to the specifications of the DUT. The
194 frequency range can also be selected using the center frequency and frequency range known as
195 the "span".
196
197 1.10.1. Select the frequency range. Choose **Stimulus Menu | Freq | Start Frequency: 1700**
198 **MHz**. Choose **Stimulus Menu | Freq | Stop Frequency: 1900 MHz.**
199
200 1.10.2. Select the measurement type (e.g., S11, S12, S21, S22). Choose **Response Menu |**
201 **Measure | S21**.
202
203 1.10.3. Select and adjust the port power. Choose **Stimulus Menu | Power | Adjust Port Power**:
204 **0 dBm**. Ensure that the output power is equal to (or below) the DUT maximum power
205 specification.
206
207 1.10.4. Select and adjust the sweep settings. Choose **Stimulus Menu | Sweep | Sweep Type**:
208 Stepped. Choose **Stimulus Menu | Sweep | time | Sweep Time: 1 sec**. Then, choose **Stimulus**
209 **Menu | Sweep | Sweep Setup | Dwell Time: 0 μsec**.
210
211 NOTE: A stepped sweep is the most accurate sweep type, as it steps to each frequency and
212 dwells at a frequency before making a measurement. If using long cables, the dwell time may
213 need to be increased to ensure that the signal arrives at the receiver after the measurement. A
214 0 μs dwell time is an optimal default setting.
215
216 1.10.5. Select and adjust averaging mode by choosing **Response Menu | Averaging |**
217 **Averaging: IFBW**: 1 kHz.
218
219 NOTE: Choose the appropriate averaging type: "point averaging" averages each frequency point
220 a number of specified times (i.e., 2, 4 16, 32, etc.), which reduces the noise floor and

221 uncertainty but increases the sweep time. IFBW uses a filter to measure the power in a small
222 bandwidth, which also reduces the noise floor but requires less measurement time. IFWB
223 averaging tends to be a more optimal averaging technique.
224
225 1.10.6. <mark>Choose the displayed data format (e.g., LogMag [default setting], Smith Chart, SWR,</mark>
226 <mark>etc.) by selecting **Response Menu | Format | LogMag**</mark>.
227
228 1.10.7. <mark>Choose the number of data points in the displayed trace using **Stimulus Menu | Sweep**</mark>
229 <mark>**| Number of Points: 1601.**</mark>
230
231 NOTE: The number of points is set so that maximal frequency coverage can be attained
232 between the start and stop frequencies:
233

$$Step\ Size\ (MHz) = \frac{(Stop\ Frequency\ (MHz) - Start\ Frequency\ (MHz))}{Number\ of\ Points - 1}$$

235
236 In the example above, the step size or frequency spacing is 0.125 MHz, so that frequency(1) =
237 1700.000 MHz, frequency(2) = 1700.125 MHz, … frequency(1600) = 1899.875 MHz,
238 frequency(1601) = 1900 MHz.
239
240 **2.** <mark>**Calibration of the VNA**</mark>
241
242 2.1. Choose a manual or electronic calibration, if an electronic calibration module is available
243 and desired (see section 2.11). Either calibration is accurate.
244
245 2.2. <mark>Choose **Manual Calibration** by selecting **Response | Cal Menu | Start Cal | Calibration**</mark>
246 <mark>**Wizard | Unguided**</mark>.
247
248 2.2.1. <mark>Choose the appropriate calibration kit so that an accurate value of the standards in the</mark>
249 <mark>specific calibration kit are known (**Figure 5**). Here, choose 85054D, then choose the two-port</mark>
250 <mark>short-open-load-thru (SOLT) calibration (for a DUT with two ports).</mark> Other available calibrations
251 are a one-port for a device with a single port, in addition to a response calibration. The SOLT is
252 the most accurate option[11].
253
254 2.2.2. <mark>Choose **Next** to go to the next screen.</mark>
255
256 2.3. <mark>Attach an open calibration standard (**Figure 6**)</mark> to the cable attached <mark>to port 1.</mark> An open
257 calibration standard has an open cavity behind the connector to simulate a free-space
258 impedance of 377 Ω.
259
260 2.4. <mark>Attach a short calibration standard to the cable attached to port 2.</mark> A short has a metal
261 plate behind the connector so that the incoming voltage is completely reflected.
262
263 <mark style="background-color:#00ff00">2.4.1.</mark> <mark>Choose **Port 1 | OPEN | Type N (50) female open**, which performs a measurement of the</mark>

264 attached open. A trace will appear on the VNA screen, gently sloping away from a 0 dB
265 reference level on a S_{11}, log-magnitude display format for the open standard. Once the
266 measurement is complete (a check mark will appear beside the standard), press the **OK** button
267 to continue. This will send the user back to the previous screen.
268
269 2.4.2. Choose a male or female calibration standard with the same sex connector as that of the
270 DUT (i.e., a male calibration standard has the center pin, and a female calibration standard will
271 have an insertable port). Older VNAs require a calibration standard based on the sex of the VNA
272 cable.
273
274 2.4.3. Choose **Port 2 | SHORT | Type N (50) female short**, which performs a measurement of
275 the attached short. A trace will appear on the VNA screen, gently sloping away from a 0 dB
276 reference level on a S_{11}, log-magnitude display format for the short standard. Once the
277 measurement is complete (a check mark will appear beside the standard), press the **OK** button
278 to continue. This will send the user back to the previous screen.
279
280 2.5. Swap calibration standards between ports (i.e., attach the open calibration standard to
281 port 2, then attach the short calibration standard to port 1).
282
283 2.5.1. Choose **Port 1 | SHORT | Type N (50) female short** to measure the short on port 1. A
284 trace will appear on the VNA screen, gently sloping away from a 0 dB reference level on a S11,
285 log-magnitude display format for the short standard. Once the measurement is complete (a
286 check mark will appear beside the standard), press the **OK** button to continue. This will send
287 the user back to the previous screen.
288
289 2.5.2. Choose **Port 2 | OPEN | Type N (50) female open** to measure the open on port 2. A trace
290 will appear on the VNA screen, gently sloping away from a 0 dB reference level on a S11, log-
291 magnitude display format for the open standard. Once the measurement is complete (a check
292 mark will appear beside the standard), press the **OK** button to continue. This will send the user
293 back to the previous screen.
294
295 2.6. Remove the short from port 1 and place a broadband load on port 1. A load absorbs the
296 incoming energy, which results in a small reflection over a large range of frequencies.
297
298 2.6.1. Choose **Port 1 | LOADS | Type N (50) broadband load** to measure the load on port 1.
299 Once the measurement is complete (a check mark will appear beside the standard), press the
300 **OK** button to continue. This will send the user back to the previous screen.
301
302 2.6.2. Keep the current calibration standard on port 2. Do not leave the port open, as it may
303 provide a path for leakage signals. A trace will appear on the VNA screen and vary across the
304 screen. All measured values on a S11, log-magnitude display format will be less than -20 dB for
305 a good load.
306
307 2.7. Remove the open from port 2, take the broadband load from port 1, and place the

308 broadband load on port 2. Place the open from port 2 on port 1 to prevent leakage signals.
309
310 2.7.1. Choose **Port 2 | LOADS | Type N (50) broadband load** to measure the load on port 2. A
311 trace will appear on the VNA screen and vary across the screen. All measured values on a S11,
312 log-magnitude display format will be less than -20 dB for a good load. Once the measurement is
313 complete (a check mark will appear beside the standard), press the **OK** button to continue. This
314 will send the user back to the previous screen.
315
316 2.8. Insert a thru calibration standard between the cables attached to ports 1 and 2. This is
317 typically an adapter with the same sex connectors on both ends.
318
319 2.8.1. Choose **THRU** to measure the thru calibration standard. Once the measurement is
320 complete, a check mark will appear above the THRU standard on this screen.
321
322 NOTE: The isolation measurement can typically be omitted during calibration as isolation
323 measures the crosstalk between cables and its value is often very small compared to other
324 standards. The calibration measurements above can be done in any order.
325
326 2.9. Once all standards have a check mark above them, save the calibration. Choose **Next |**
327 **Save as User Calset**. Enter a name for the calibration and press the **SAVE** button.
328
329 2.10. Check the calibration as detailed in section 3.
330
331 2.11. If a manual calibration is not chosen, choose the electronic calibration option[12]. Attach
332 the electronic calibration kit (**Figure 7**) to the cables between ports 1 and 2. Select **Response |**
333 **Cal Menu | Start Cal | Calibration Wizard | Electronic Calibration** with the electronic
334 calibration option.
335
336 2.11.1. Choose **2-port ECal | Next**, then select the **Measure** button. The electronic calibration
337 module will automatically measure a number of different standards and prompt the user to
338 save the calibration at the end.
339
340 2.11.2. Choose **Next | Save as User Calset**. Enter a name for the calibration and press the **SAVE**
341 button.
342
343 NOTE: For an electronic calibration only the cables from ports 1 and 2 are connected to the
344 module. All calibration standards are contained in the module. The electronic calibration will
345 calibrate the internal standards automatically. If the electronic calibration module does not
346 have the same connector types as the cables, then an additional calibration will need to be
347 completed to modify the calibration error corrections contained within the module to account
348 for the adapters. Make sure to check with the manufacturer for guidance.
349
350 **3. Checking the calibration**
351

352   3.1. Use a thru to check the calibration.

354   3.1.1. Connect a thru adapter (**Figure 6**) without obvious signs of wear to the cables between
355   ports 1 and 2. Do not measure the thru standard. Choose a different thru.

357   3.1.2. Choose **Response | Measure | S21**, then **Response | Scale | Scale.** Set the **Per Division**
358   value to 0.1 by pressing the down arrow button. Choose **Stimulus Menu | Trigger | Single** to
359   measure the insertion loss of the thru. A single sweep will appear across the frequency range.

361   NOTE: The value of the thru on a log magnitude plot lies within 0.05 dB of the 0 dB reference
362   (**Figure 8**) for sufficient calibration. This is an empirical value obtained over many years of
363   calibrations. This can be seen by changing the scale to 0.05 dB per division.

365   3.1.3. Once the thru has been checked, return the scale back to 10 dB/division by choosing
366   **Response | Scale | Scale** and set the **Per Division** value to 10. Choose **Response | Measure |**
367   **S11.**

369   3.1.4. Choose **Stimulus Menu | Trigger | Single** to measure S11. The value of a good thru is the
370   following: |S11| = -20 dB (1% reflection in power and 10% reflection in voltage).

372   NOTE: The Smith Chart[13] representation displays impedance. Measurements of S11 and S22
373   appear as a small circle in the center of the chart. The impedance value is within 0.5 Ω from the
374   50 Ω reference for sufficient calibration.

376   3.2. Use a 50 Ω load to check the calibration.

378   3.2.1. Attach a 50 Ω matched load to the port 1.

380   3.2.2. Choose **Stimulus Menu | Trigger | Single** to measure S11.

382   NOTE: A matched load is less than -20 dB (the reflection coefficient of an ideal load is 0). This
383   will also appear as a small circle at the center of the Smith Chart (**Figure 9**).

385   3.3. Use an open calibration standard to check the calibration.

387   3.3.1. Connect an open calibration standard.

389   3.3.2. Choose **Stimulus Menu | Trigger | Single** to measure S11. An open is 0 dB on a log-
390   magnitude plot (the reflection coefficient of an ideal open is 1). On a Smith Chart, the open
391   appears as a small circle at 0 on the far right (**Figure 9**) for sufficient calibration.

393   3.4. Use a short calibration standard to check the calibration.

395   3.4.1. Connect a short calibration standard.

396
397 3.4.2. **Choose Stimulus Menu | Trigger | Single** to measure S11. A short is 0 dB (the reflection
398 coefficient of an ideal short is -1) on the log-magnitude plot. On the Smith Chart, the value
399 appears as a circle on the far left (**Figure 9**) for sufficient calibration.
400
401 NOTE: If a calibration test fails, check the connections and repeat the calibration. If the
402 calibration is good, continue to section 4.
403
404 **4. Measurement of components or system losses**
405
406 4.1. Connect the DUT to the VNA. If the DUT has more than two ports (i.e., switches, power
407 dividers, etc.), attach 50 Ω matched loads to the ports that are not connected to the VNA, as
408 power will be reflected from these ports and change the measurement.
409
410 4.2. Select **Response | Measure | S21.**
411
412 4.3. Select **Stimulus Menu | Trigger | Single** to measure the DUT.
413
414 4.4. Select **File | Save Data As…** . Type in a file name in the file name box. Choose a file type of
415 either .CSV or Trace (*.s2p). Choose the **Scope** (the default value of **Displayed Traces** is
416 appropriate here). Choose a **Format** (e.g., log magnitude and angle, linear magnitude and
417 phase, real and imaginary, and displayed format [such as a Smith Chart]). Press **SAVE** to save
418 the data.
419
420 4.5. Check and analyze the test results of a bandpass filter. An example is outlined in the
421 following steps.
422
423 4.5.1. Identify parts of the trace by placing markers on the trace. Select **Marker/Analysis |
424 Marker | Marker 1** and press **OK**.
425
426 4.5.2. Select **Marker/Analysis | Marker Search | Max** to find the insertion loss of the trace
427 filter. The knob on the front panel can also be used to identify maxima and minima while
428 sweeping the marker across frequency points.
429
430 4.5.3. Select **Marker/Analysis | Marker < Marker 1**, then select **delta marker** and **coupled
431 markers**. The value of this marker as shown on the screen should read 0 dB. This will set a
432 reference value for the other markers.
433
434 4.5.4. Select **Marker/Analysis | Marker… | Marker 2 | ON | coupled markers**. Click inside the
435 stimulus box to highlight the frequency, then move the knob until the reading of Marker 2 on
436 the screen shows -3 dB.
437
438 4.5.5. Select **Marker/Analysis | Marker… | Marker 3 | ON | coupled markers**. Click inside the
439 stimulus box to highlight the frequency and move the knob until the reading of Marker 3 on the

440 <mark>screen shows -3 dB.</mark>

441

442 4.5.6. Compare the measured values to those of the manufacturer's filter specifications.

443

444 **REPRESENTATIVE RESULTS:**

445 When verifying whether a component is operating correctly, it is important to consult the

446 manufacturer's specifications, which can be found on their respective websites. Here, the filter

447 (**Figure 10**) was measured after consulting its specifications[14]. As shown in **Figure 11**, the

448 insertion loss was identified, as well as the 3 dB points. The measured insertion loss after

449 calibration, as shown by marker 1, had a magnitude of 0.83 dB. The negative sign indicates that

450 it was a loss. The insertion loss in the reference is specified to be 0.8 dB adjusted (dBa). The

451 measured 3 dB bandwidth of the filter changed from 1,749 MHz to 1,854 MHz. When

452 subtracted, this yielded a value of 105 MHz, which is close to the typical value of 104.5 MHz.

453

454 There are 10 dB attenuators built to withstand an input power of 50 W, as described by the

455 manufacturer's specifications[15]. The attenuation specification for this attenuator is 10 dB ± 0.5

456 dB. At some point, an input power greater than 50 W was input into the attenuator, which

457 damaged the attenuator. A calibrated VNA was used to check the quality of this component.

458 Again, it is important to measure each component before all field measurements for quality

459 assurance. Measurement of the DUT is shown in **Figure 12**. In comparison, measurement of a

460 good 10 dB attenuator is shown in **Figure 13**. It should be noted that the measured value was

461 9.88 dB at 1,750 MHz, which is within the specified range of -9.5 to -10.5 dB across the entire

462 bandwidth of 1,700–1,900 MHz.

463

464 Finally, cable loss is another important measurement frequently performed in radio frequency

465 measurements. Specifications for the measured cable can be found on page 5 of the data

466 sheet[16]. The attenuation per foot (dB/ft) was 0.05 dB at 1 GHz, or 0.16 dB/m. A measured cable

467 with a length of 36 feet/11 m had a specified loss of ~1.8 dB, according to the manufacturer.

468 The measured loss is shown in **Figure 14**. At a frequency of 1,750 MHz, the measured loss was -

469 1.88 dB (which, when rounded up to the nearest tenth of a decibel, is a magnitude of 1.9 dB).

470

471 **FIGURE LEGENDS:**

472

473 **Figure 1: Turning on the VNA.** The red circle represents the location of the VNA power button.

474

475 **Figure 2: High quality, phase-stable cables attached to two VNA ports.** The cables are attached

476 to the front panel of the VNA using an 8 in.lbf. torque wrench.

477

478 **Figure 3: Cleaning connectors**. (**A**) Cleaning of the inner conductor, (**B**) cleaning of the outer

479 conductor and threads, and (**C**) gently blow drying the connector using compressed air.

480

481 **Figure 4: A 12 in.lbf. torque wrench for type N connectors.** This wrench is used to tighten

482 connections between the VNA cables and DUT.

483

484   **Figure 5: Type N calibration kit.** Shown here is a calibration kit containing open, short, load,
485   and thru standards used to calibrate errors in the VNA.
486
487   **Figure 6: Type N calibrations standards.** Photographs of the male and female calibration
488   standards used in the calibration.
489
490   **Figure 7: Electronic calibration module.** A photograph of an electronic calibration module.
491
492   **Figure 8: Thru calibration check after calibration on a log-magnitude plot as a function of**
493   **frequency in GHz.** The value of the thru is 0.01 dB at a frequency of 1.8 GHz. This shows the
494   value of the thru as a function of frequency in GHz after calibration. The thru is used as a
495   calibration check to ensure that the calibration is valid.
496
497   **Figure 9: Smith Chart explanation.** Real and imaginary impedance value locations for standard
498   impedances are shown in the left-hand figure, and impedance magnitude values are shown in
499   the right-hand figure[17]. This Smith Chart drawing shows both the real and imaginary impedance
500   on the left and impedance magnitude on the right.
501
502   **Figure 10: RF filter inserted between ports 1 and 2.** A photograph of an RF filter inserted
503   between ports 1 and 2 at the end of the VNA cables during measurements.
504
505   **Figure 11: Measured insertion loss and 3 dB points for RF filter with specifications provided in**
506   **Figure 9.** This is a screenshot from the VNA during measurement of the RF filter that is shown in
507   **Figure 10.**
508
509   **Figure 12: Measurement of 10 dB attenuator not within its specifications.** The measured value
510   is -22.70 dB at 1.7 GHz and its specification is 10 dB ± 0.5 dB. Also shown is measurement of a
511   10 dB attenuator that is no longer within its specifications.
512
513   **Figure 13: Measurement of 10 dB attenuator within its specifications**. The measured value
514   was -9.88 dB. Also shown is measurement of a 10-dB attenuator that is within its specifications.
515
516   **Figure 14: Measurement of 36 ft (11 m) coaxial cable with a 0.05 dB/ft specified attenuation**
517   **value**. Loss through the length of the cable was expected to be ~1.8 dB, which is consistent with
518   the measured value of -1.9 dB at 1.87 GHz. Also displayed is measurement of a cable showing
519   that the measured loss is within the manufacturer's specifications.
520
521   **DISCUSSION:**
522   It is important to allow the VNA to warm to RT for at least 0.5 h (although, 1 h is better) before
523   calibrations are performed, which allows all internal components to come to RT and results in
524   more stable calibrations. One calibration can last several days without a large loss of accuracy;
525   however, the calibration is checked daily using a calibration standard to ensure integrity of the
526   measurement. Inspection of all system components is essential so that bad connectors do not
527   damage the precision of the VNA. It is best to use low loss cables with the VNA. The integrity of

528 the calibration must be checked before the measurement of any system component or DUT.
529 Any measurement outside the specifications provided here should be repeated or may require
530 a new calibration. Finally, using the manufacturer's specifications to check the measured DUT
531 values is a necessary part of validation.
532
533 Using the VNA as a measuring instrument has its limitations. If the DUT or system has losses so
534 large that the measured S-parameters fall below the noise floor of the VNA, it cannot be
535 measured with the VNA. It is possible to lower the noise floor by decreasing the IF bandwidth
536 and increasing the sweep time. This will slow down the measurement acquisition time; thus,
537 there is a trade-off when adjusting these parameters. The VNA cannot handle input powers
538 greater than 30 dBm, so using internal or external attenuation when measuring amplifiers is
539 required. The VNA has a source and receiver located in the same instrument, so it has been
540 used as a radio propagation measurement system. Because the source and receiver are located
541 in the VNA, the transmitting port must be joined in some manner to the receiving port.
542 Typically, this is done with cables; however, cables add loss, decreasing the dynamic range of
543 what can be measured. Furthermore, separation distances become limited.
544
545 The other method by which losses can be measured is use of a signal generator and power
546 meter. The power meter is a scalar measurement device, so it can only measure a signal's
547 magnitude. It cannot monitor the phase of the signal, which results in less accurate
548 measurements of the signal. The VNA measures both the magnitude and phase (of real and
549 imaginary components) of a measured signal relative to a well-known input signal, which is a
550 higher quality measurement.
551
552 VNAs are a versatile option for many types of measurements. The instrument can be used to
553 measure radiated radio signals using antennas on the transmitting and receiving ports[18]. Time
554 domain analysis can be used to monitor signals over time and determine where a break occurs
555 in a cable. It can measure many frequencies during a sweep, which can be used to understand
556 attenuation losses over many frequencies either in a conducted[19] or radiated environment[20].
557 Understanding the various parameter settings of the VNA results in well-characterized
558 DUTs/systems, and measurements obtained with the DUT/system can be used with a high
559 degree of confidence.
560
563
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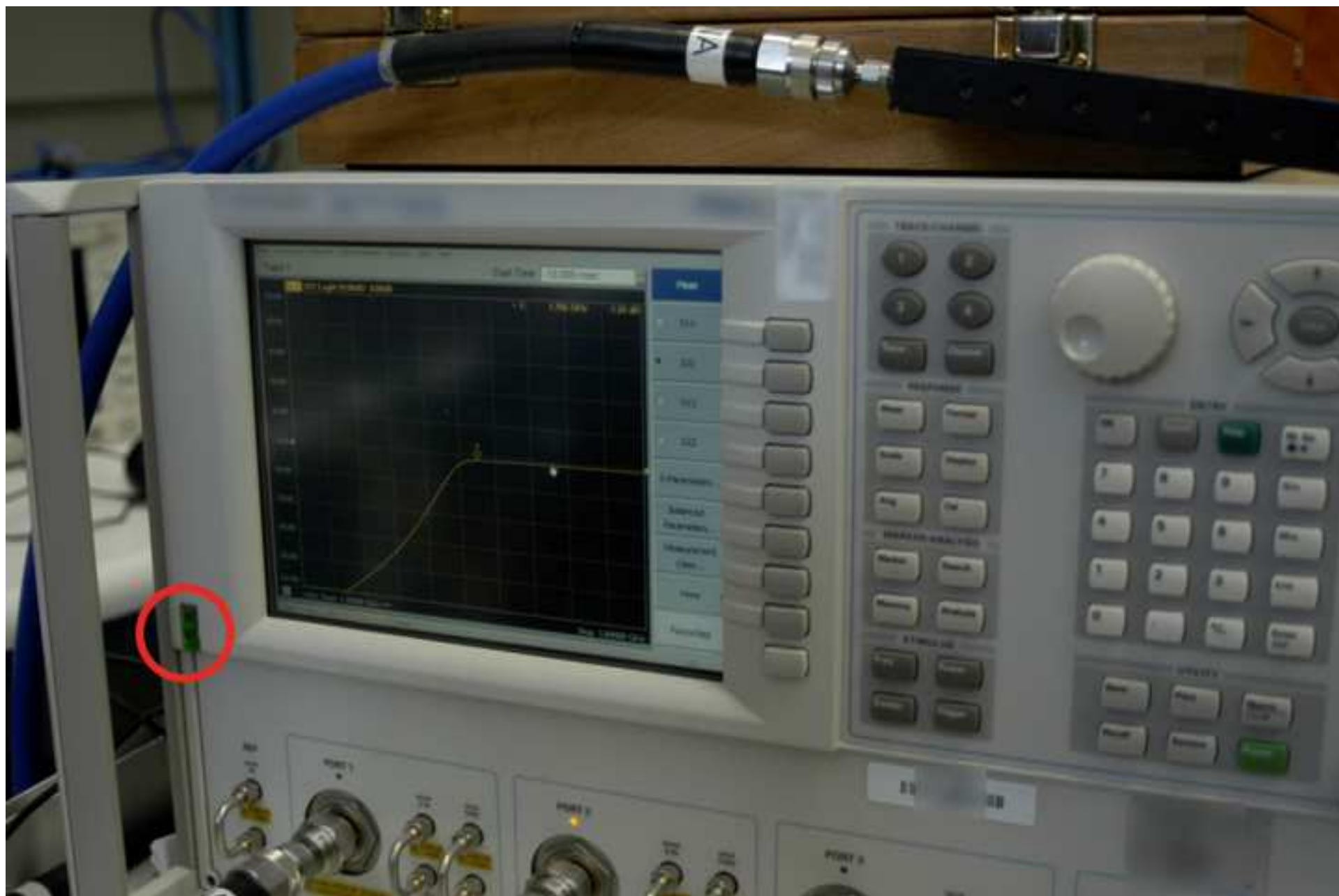
(a) Inner conductor

(b) Outer conductor

(c) Blow dry

Figure

	Male	Female
Open		
Short		
Load		
Thru		

$$Z_0$$

$$V_{incident}$$
$$V_{reflected}$$

$$Z_L$$
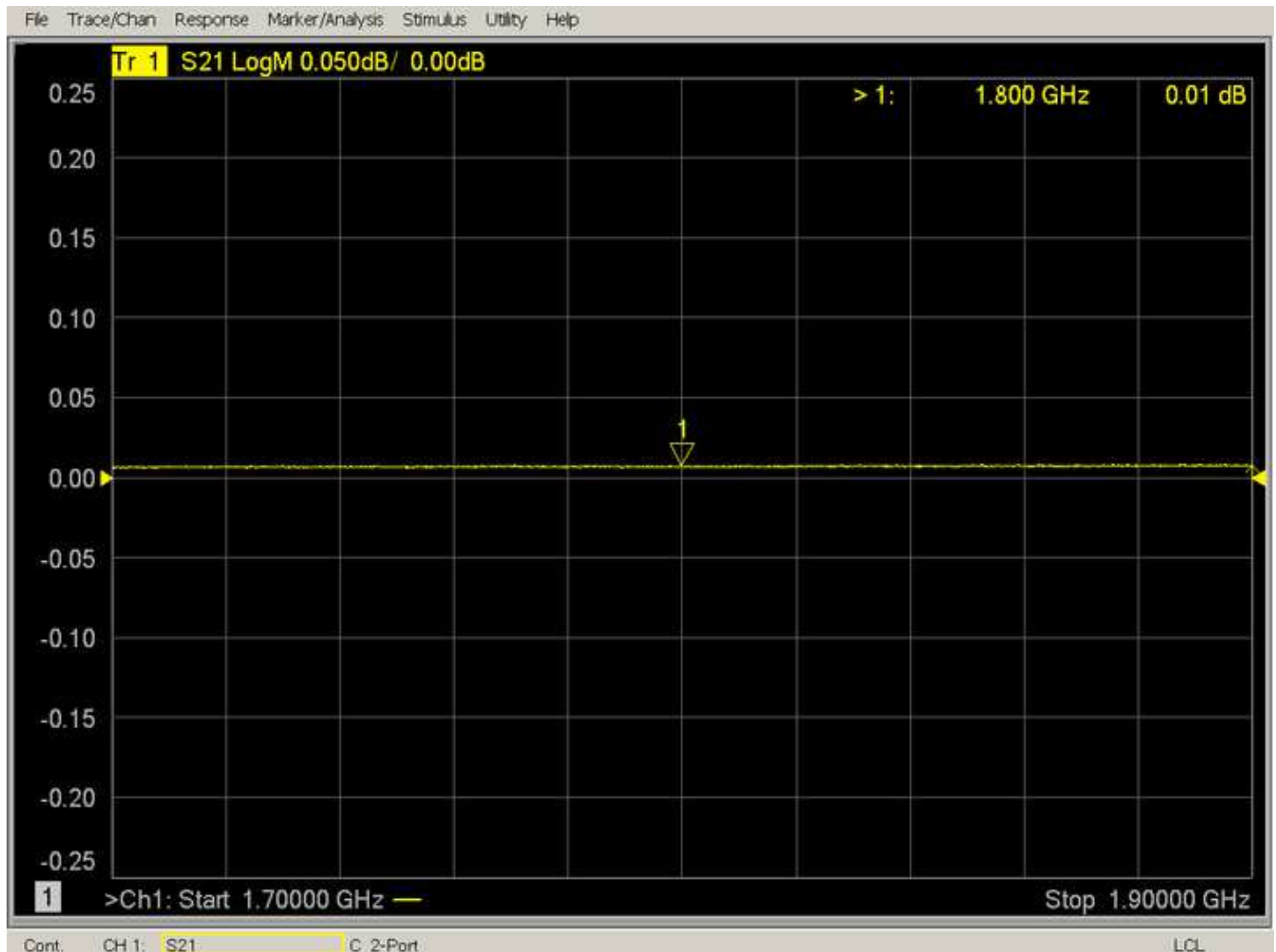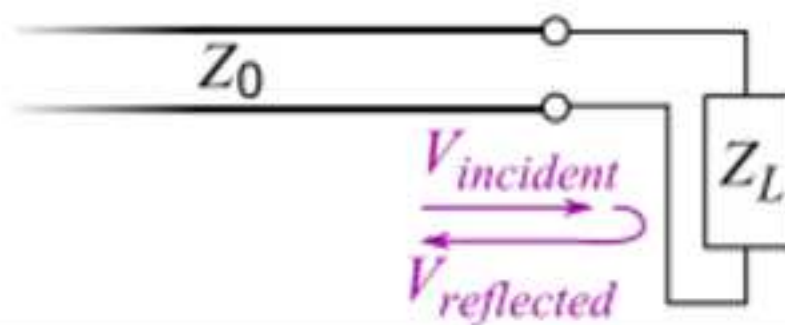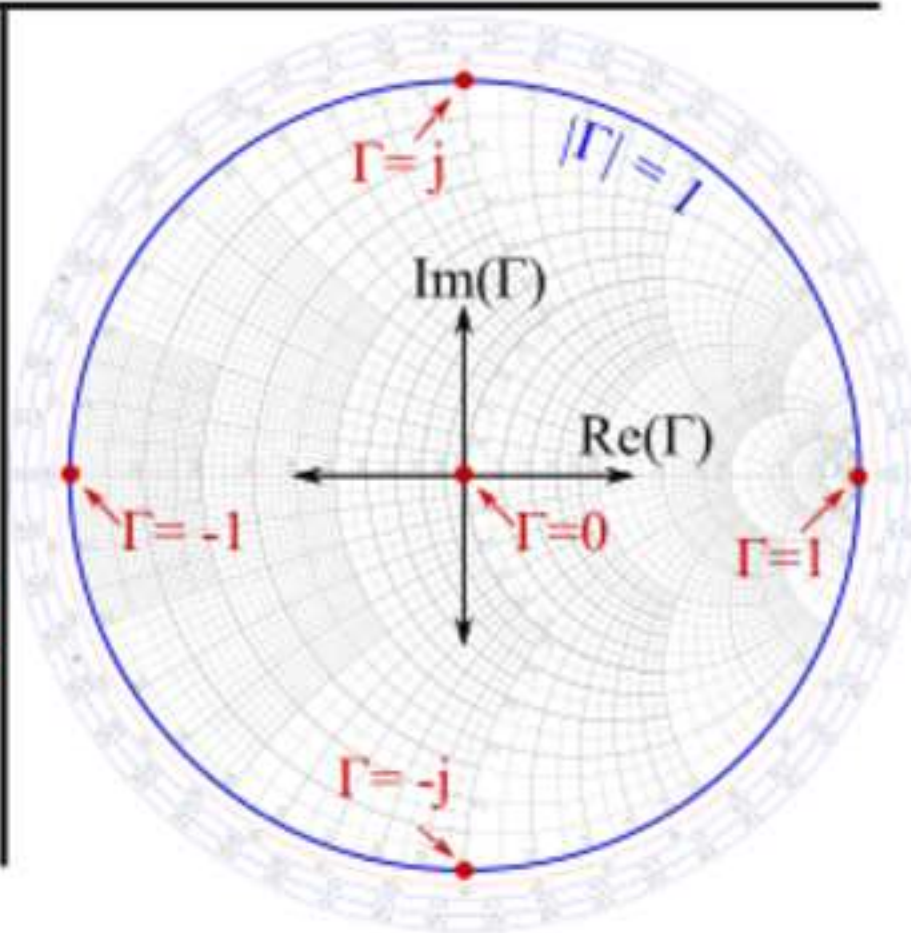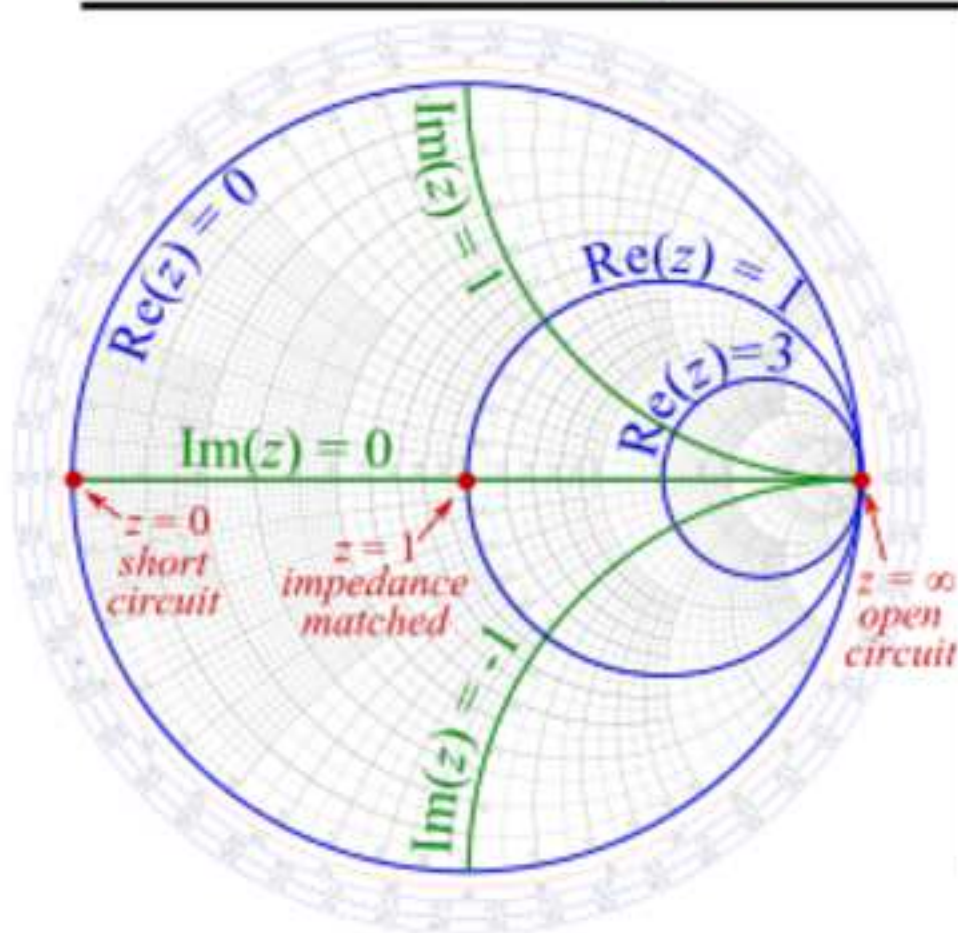
$$z = \frac{Z_L}{Z_0}$$
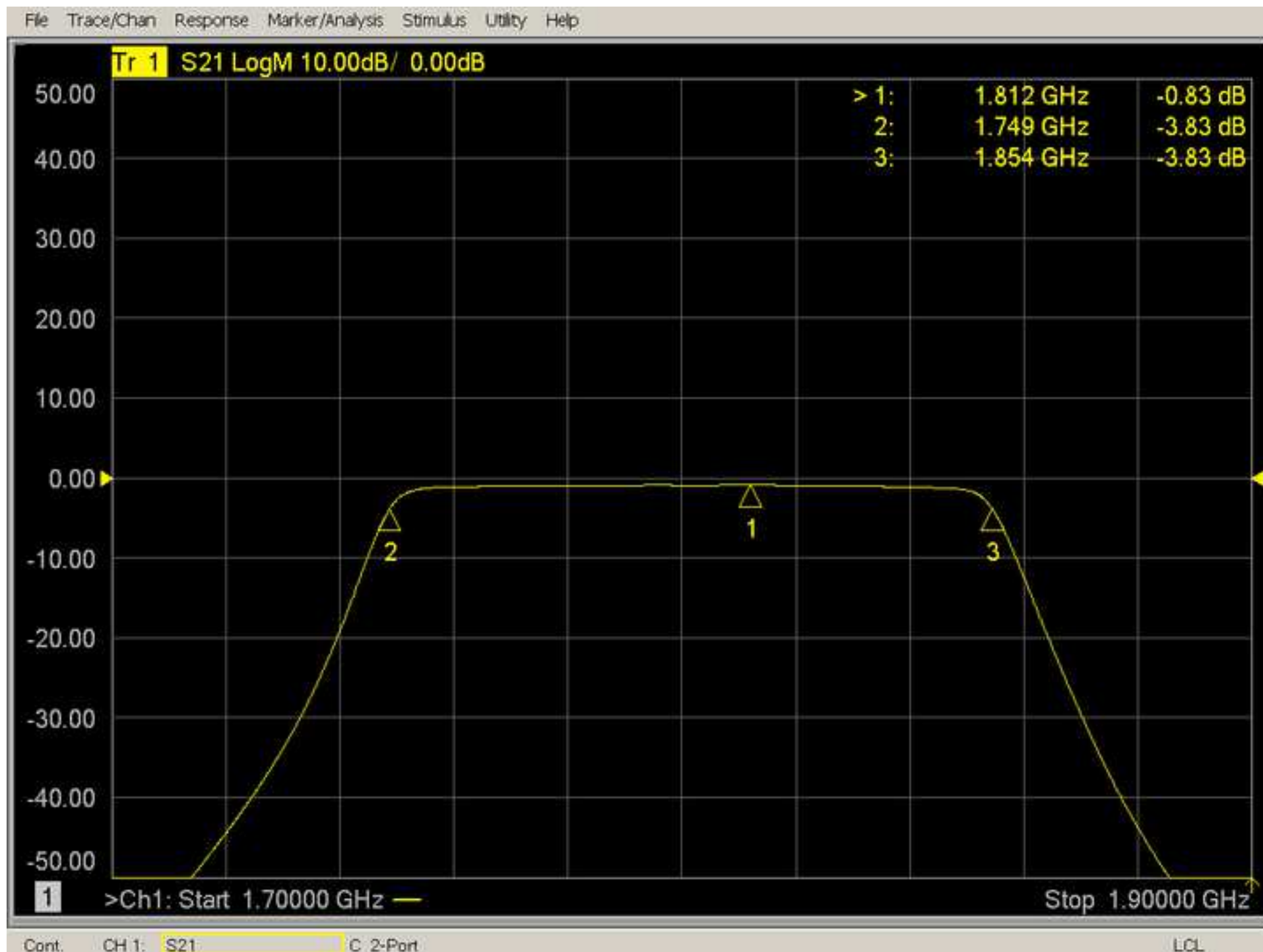
$$\Gamma = \frac{V_{reflected}}{V_{incident}}$$

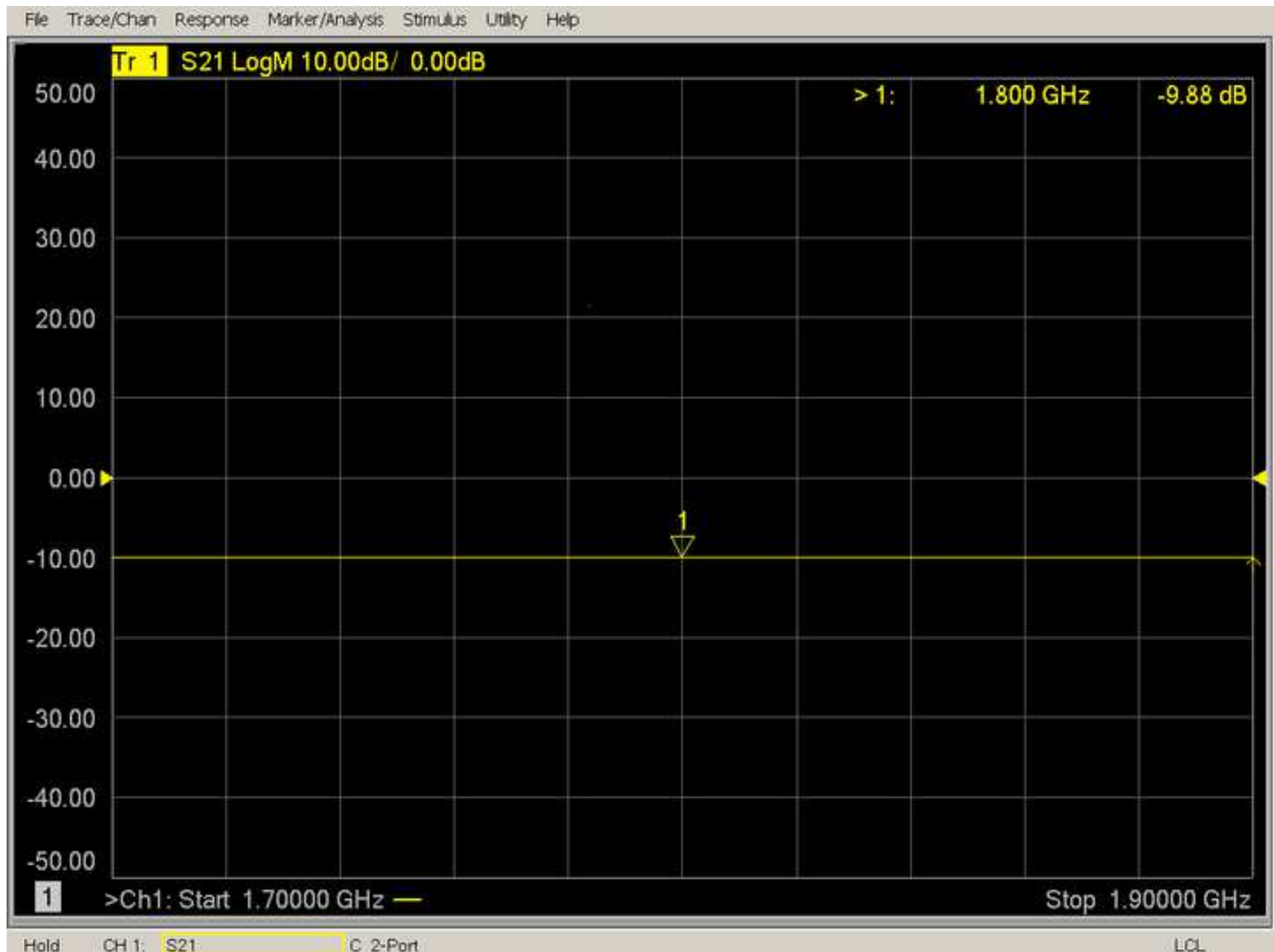$Re(z) = 0$

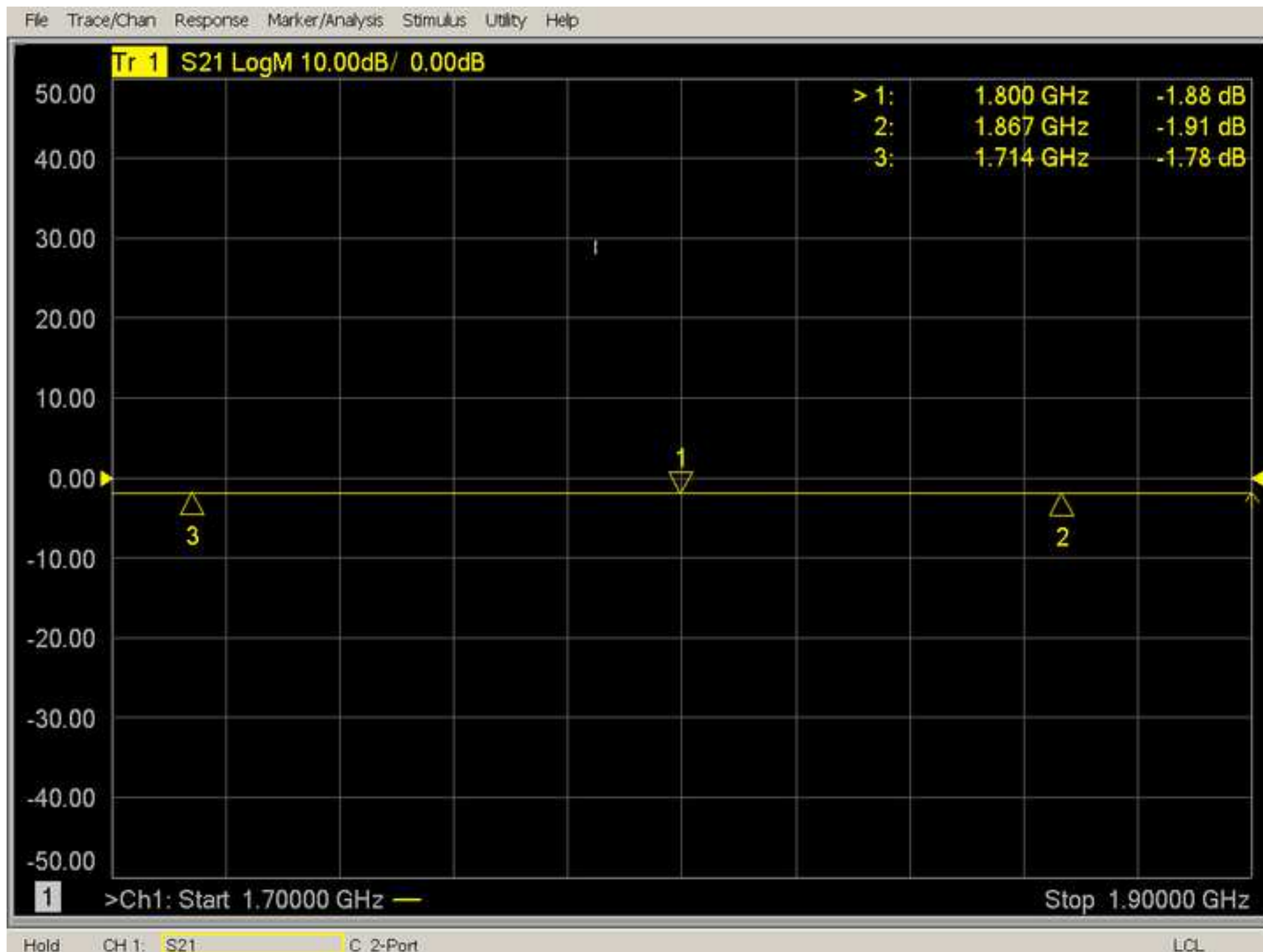$Im(z) = 1$

$Re(z) = 1$

$Re(z) = 3$

$Im(z) = 0$

$z = 0$
short circuit

$z = 1$
impedance matched

$z = \infty$
open circuit

$Im(z) = -1$

$\Gamma = j$

$|\Gamma| = 1$

$Im(\Gamma)$

$Re(\Gamma)$

$\Gamma = -1$

$\Gamma = 0$

$\Gamma = 1$

$\Gamma = -j$
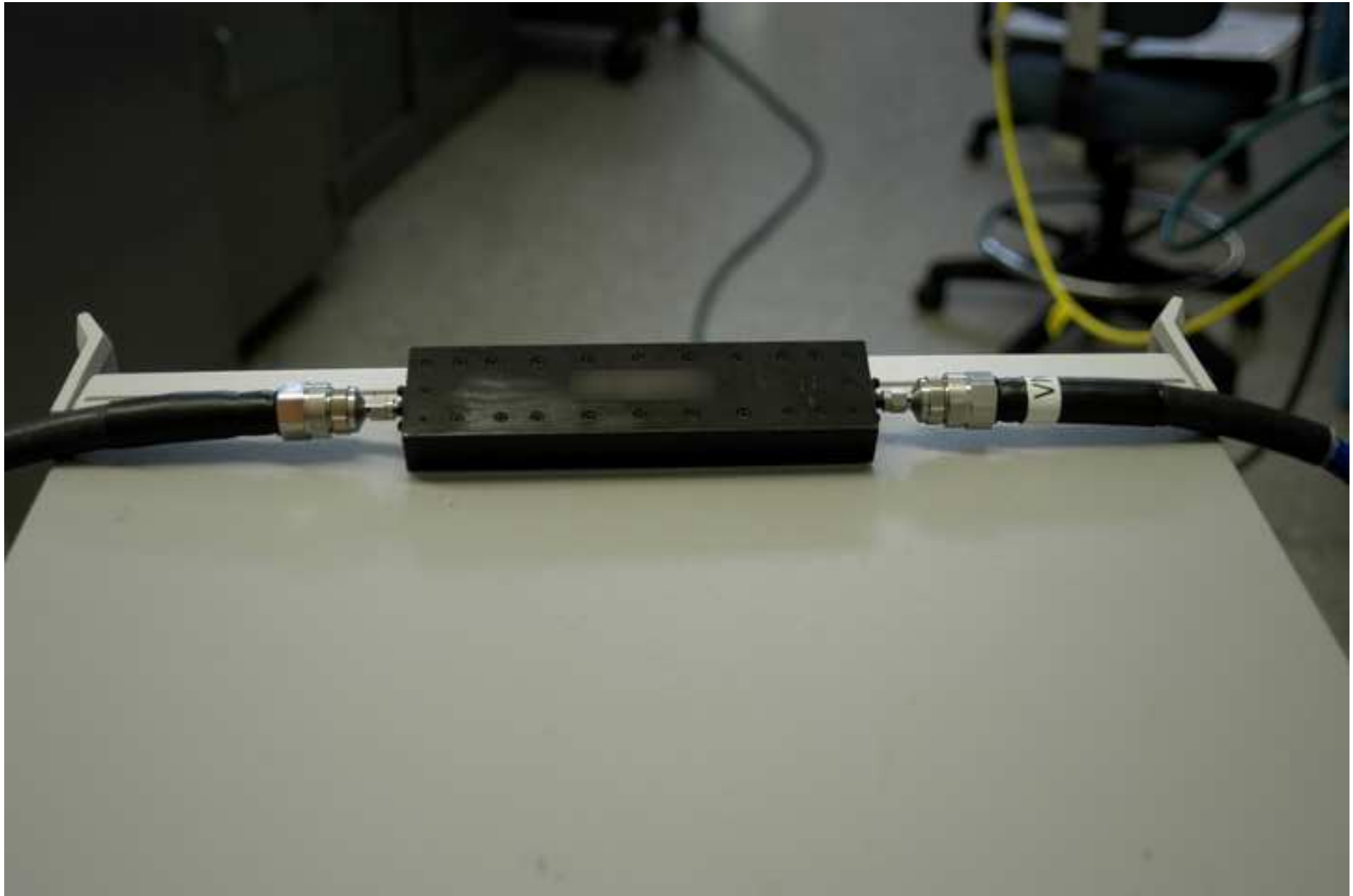
Figure10-Filter.jpg

Figure

Name of Material/Equipment	Company	Catalog Number	Comments/Description
12 inch-pound torque wrench	Maury Microwave		TW-12
8 inch-pound torque wrench	Keysight Technologies		8710-1764
Attenuators	Mini-Circuits		BW-N10W50+
Cable 1	Micro-Coax		UFB311A – 36 feet
Calibration Standard Set (1) (manual)	Keysight Technologies		Economy Type-N Calibration kit, 85054 D
Calibration Standard Set (2) (E-cal)	Agilent Technologies		Electronic Calibration Kit, N4693-60001, 10 MHz to 50 GHz
Cleaning Swab	Chemtronics		Flextips Mini
Compressed Air	Techspray		Need ultra filtered
Filter 1	K&L Microwave, Inc.		8FV50-1802-T95-O/O
Isopropyl Alcohol	Any brand		
VNA	Keysight Technologies		There are many options available for a researcher – please consult the website

Revisions to editorial comments
December 16, 2019

Protocol, Step 1. VNA Setup

Reviewer: I added this as a subheading for better organization. I've also extended the highlighting for continuity and completeness. (my additions are in green).

Hammerschmidt: This is okay with me. I didn't know how much detail you needed as this is my first publication/presentation with JoVE.

Protocol, Step 1.4

Reviewer: Can you specify which ports exactly?

Hammerschmidt: I have specified ports 1 and 2.

Protocol, Step 1.9

Reviewer: Please specify which ports are connected.

Hammerschmidt: Specified ports 1 and 2.

Protocol, step 2.4 to step 2.11

Reviewer: How is the measurement taken? Unclear what exactly is done here.

Hammerschmidt: Had to rearrange some of the steps to make sure the steps are done correctly and in the right order. I think I have clarified comments in steps 2.4 to 2.11, with sub-bullets.

Protocol, Step 3.1 to step 3.4

Reviewer: How?

Hammerschmidt: I have tried rewording and adding steps to make this clearer.

Protocol, Step 4.1 to step 4.4

Reviewer: Unclear what is done here, please add the necessary details.

Hammerschmidt: Have added additional working to clarify.

Reviewer: What specifications?

Hammerschmidt: Added wording to state the manufacturer's specifications.

FIGURE LEGENDS, Line 559

Reviewer: Use superscripted reference and add this to the reference list.

Hammerschmidt: Added to References and superscripted the reference.

<u>REFERENCES, Reference 3</u>

Reviewer: Please complete the reference.

Hammerschmidt: Deleted because this is not forthcoming and no timeline has been determined.