**Filter Measurements with a Vector Network Analyzer**

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## 1. Introduction

Filters are very common and important components in any radio system. They are used to eliminate or reduce undesired signals and harmonics or to alter the amplitude and phase response of a circuit. Whether you build your own or buy packaged filters, it is necessary to verify their intended performance and characteristics. For radio frequency applications, a vector network analyzer (VNA) is a suitable instrument for this purpose.

In the following sections I briefly review the types of measurements that can be made with a VNA and the need for VNA calibration. I demonstrate actual measurements with three identical bandpass filters having a nominal frequency range of 2 to 32 MHz. I use these as preselection filters for reducing out-of-band radio frequency interference (RFI) at the input of HF receivers for solar and Jupiter radio burst detection and HF propagation studies (figure 1). I previously described an inexpensive VNA designed by Tom Baier and produced by SDR-Kits, called the VNWA-3E, and a shop-built S-Parameter Test Set of my own design (figure 2) (Reeve-SPTS}. I use these instruments for the measurements.

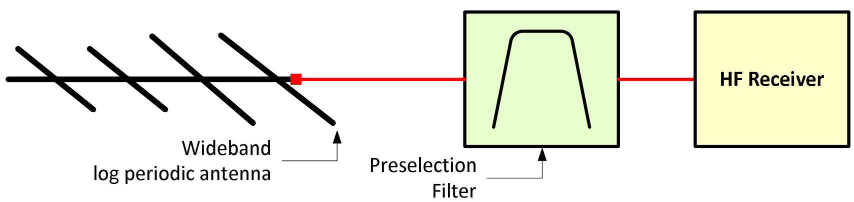



Figure 1 ~ Typical preselection filter application in which the filter is placed between the antenna and receiver to reduce out-of-band interference. Image © 2016 W. Reeve

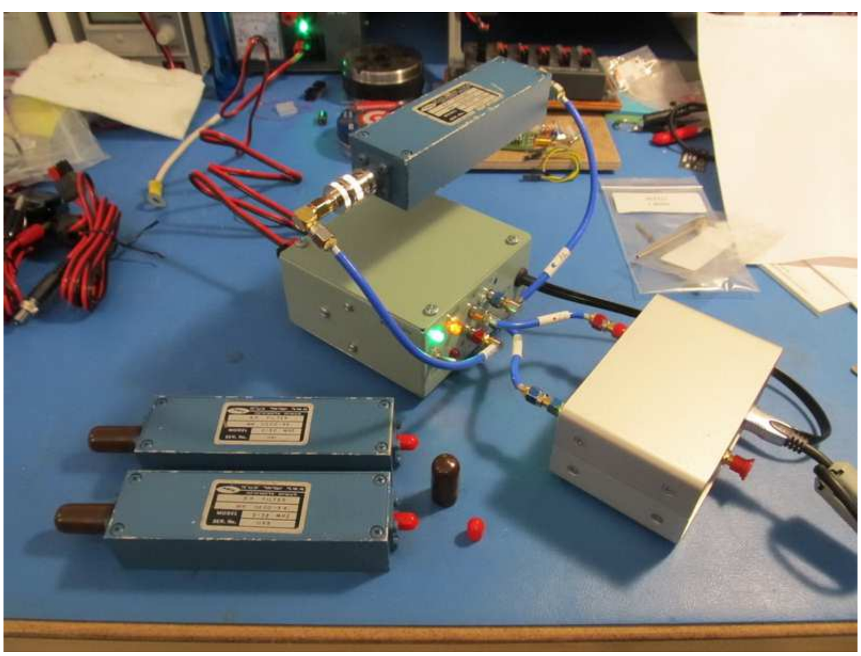


Figure 2 ~ Vector network analyzer hardware. The VNWA-3E is the silver box in the lower-right corner and the S-parameter test set is the sage green box to its left. One filter (blue box) is connected and suspended above the S-parameter test set and two additional filters are shown to the lower-left. Not shown is the PC that controls and powers the VNWA-3E through its USB port. The S-Parameter Test Set is powered by a separate 28 Vdc power supply. Image © 2016 W. Reeve

## 2. VNA measurements

The basic measurement functions of a VNA produce voltage and current ratios but most VNAs display the results in various forms, such as

- S-parameters: reflection coefficients – forward (s11) and reverse (s22) path reflection and transmission coefficients – forward (s21) and reverse (s12) path transmission (isolation)
- Return loss (dB)
- Insertion gain or loss (dB)
- Complex impedance (R + jX) or admittance (G + jB)
- Impedance magnitude and phase (|Z| $\angle\theta$ )
- Voltage standing wave ratio, VSWR
- Smith Chart

Although the VNWA-3E has more capabilities than listed above, I discuss only the s-parameters and Smith Charts in this paper.

<u>S-Parameters</u>: S-parameters are one way of describing the electrical characteristics of RF devices such as filters, antennas and amplifiers. There are four parameters and each is a ratio of the signal incident on a device to the signal that is reflected by the device or transmitted through it (figure 3). VNAs usually measure voltages and currents but then display the measurements as power ratios or impedances with respect to frequency in a rectilinear (rectangular) plot (figure 4).

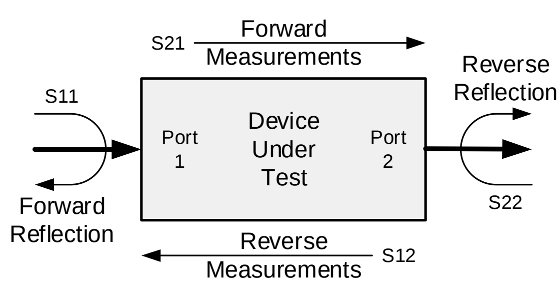



Figure 3 ~ Block diagram showing incident, reflection and transmission directions. For example, S11 is the ratio of incident voltage to reflected voltage on port 1 when port 2 is terminated in its characteristic impedance. Image © 2013 W. Reeve

For a thorough discussion of s-parameters, see [HP] and for discussion of vector network analyzers, see [Agilent] and [Anritsu]. For complete books, see [Dunsmore] and [Hiebel]. For an original description of the mathematical basis for s-parameters, see [RadLab8].

<u>Smith Charts</u>: The same measurements used to produce the s-parameter charts previously described are used to produce Smith Charts. In other words, the rectilinear s-parameter plots and Smith Charts show the same information but in different formats. However, the Smith Chart does not have a frequency scale and most often is used for impedance matching.

The Smith Chart is a graphical method for displaying reflection and transmission parameters (figure 5). It is a form of circular transmission line chart that shows all possible impedance, admittance or reflection coefficient values of a transmission line or circuit. The chart uses families of circles and arcs to represent these parameters.

The circles represent the values of constant resistance and the arcs represent the values of constant reactance. All values of reactance and positive resistance from zero to infinity are represented on the outer circle. One advantages of a Smith Chart is that it displays infinity as a chart value, something not possible on a rectilinear plot.

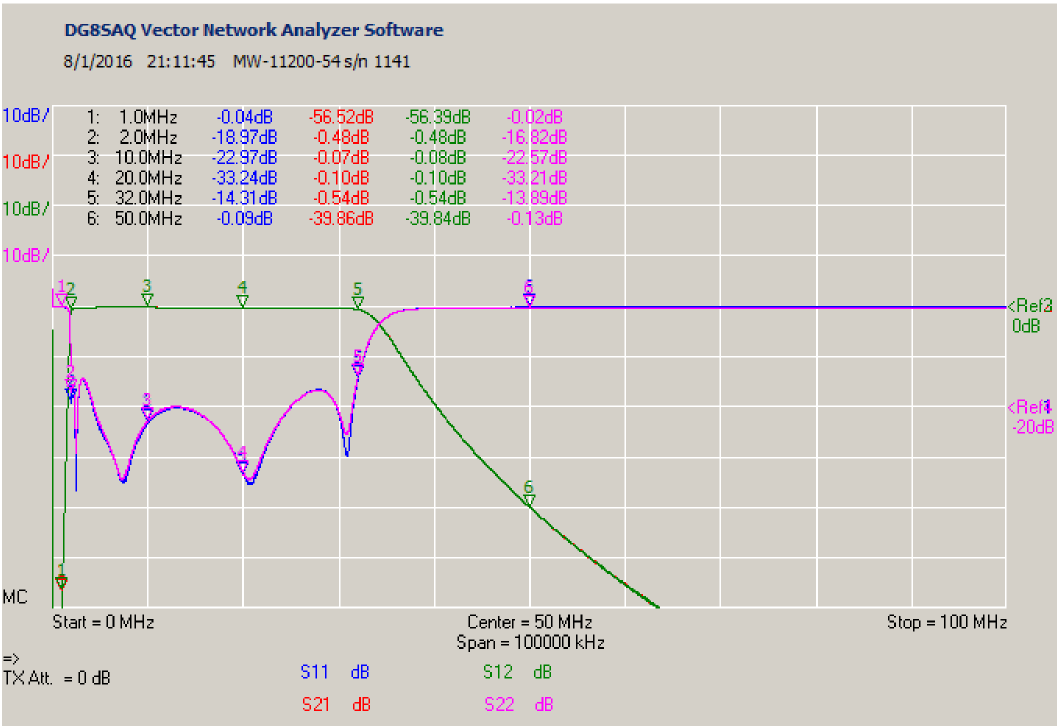



Figure 4 ~ Typical s-parameter plots from the VNWA-3E analyzer. The vertical scale shows dB. The 6th division is the 0 dB reference. The horizontal scale is frequency from 0 to 100 MHz. The s-parameters and their corresponding trace colors are indicated at the bottom. The marker table at the upper-left shows the marker frequency and corresponding values for each trace. This plot has four traces but two are hidden underneath another trace.

A typical Smith Chart is normalized to the system impedance. All Smith Charts in this paper are normalized to 50 ohms impedance. A perfect match is located at the center of the chart and, thus, its normalized value is 1.0. The left edge of the Smith Charts used here is zero (0) impedance and the right edge is infinite $(\infty)$ impedance. Since the Smith Chart does not have a frequency scale, markers are necessary to indicate values at different frequencies. Filter and transmission line impedance matching is a common use of the Smith Chart. For more information on the Smith Chart, see [Smith] and {MW101} and {SSS}.

### 3. VNA calibration

User calibration is an important aspect of using any VNA. Calibration corrects for imperfections in the instrument, test cables, adapters and fixtures and also the environment in which the VNA is used. Most professional VNAs have a built-in factory calibration that is valid at the instrument's test ports; however, user calibration is needed if a device is not connected directly to those ports or if higher accuracy is needed. The VNWA-3E does not have a built-in calibration, but its software automatically reloads the last used calibration if one exists. However, this calibration may not cover the desired frequency range for the current measurements, so for best accuracy the VNWA-3E must be recalibrated prior to use.

The most common type of calibration uses Short, Open, Fixed-termination (Load) and Thru calibration standards, denoted SOLT. These are precision components placed, in turn, on the VNA port cables during calibration and then set aside. The calibration data is stored in a file, and the calibration components are not used during the measurements of a device. The calibration can be made over the frequency range of interest if less than the VNA's entire frequency range or over the entire range of the VNA and then the frequency reduced for device measurement; the former method provides the best accuracy. A new calibration is needed if measurements are to be made at frequencies outside the range of the original calibration, and a new calibration is needed if the frequency sweep mode is changed from linear to logarithmic or back. For the measurements described here, I used a Rosenberger model NA-EC1 EcoCal standards kit available from Heuermann HF-Technik in Germany {Cal} (figure 6).

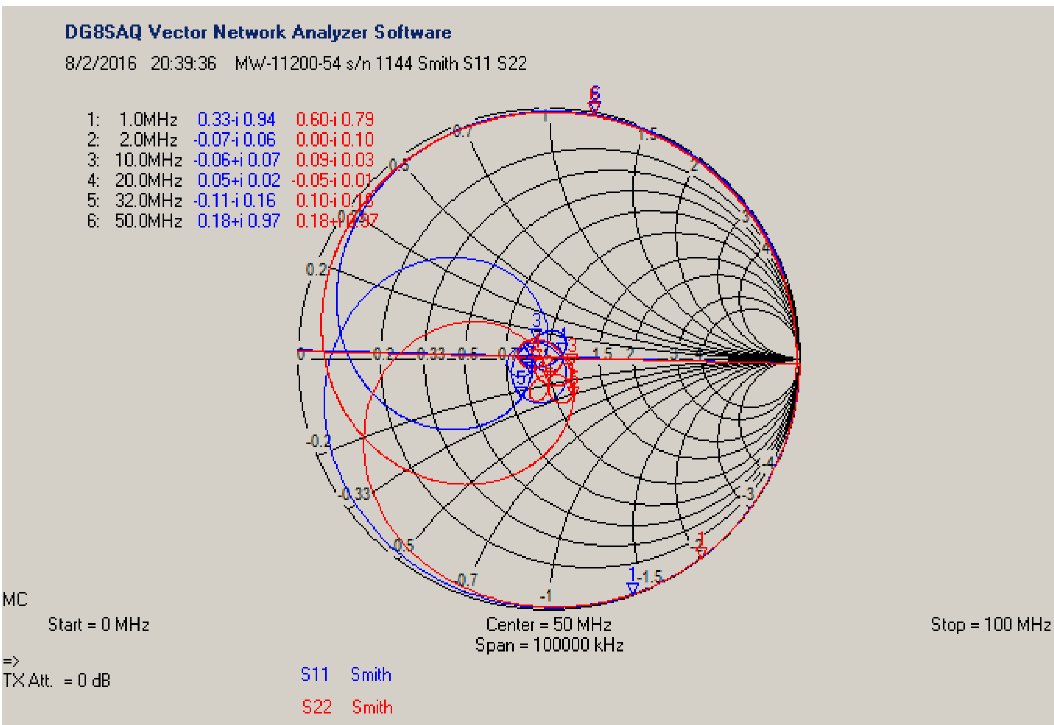



Figure 5 ~ Typical Smith Chart from the VNWA-3E analyzer. The black lines are the grid. The blue and red traces show the input (s11) and output (s22) normalized impedance over the frequency range indicated. The normalized impedance is at chart center so the traces near the center indicate a good match (low reflection coefficient) and traces along the periphery indicate a poor match. Although the grid is based on normalized impedance (inductive reactance at top, capacitive reactance at bottom) the marker table indicates reflection coefficients.

When used to make bidirectional measurements on a 2-port device, the calibration process requires ten separate steps, five in the forward direction (FWD) and five in reverse (REV):

- Short, FWD and REV
- Open, FWD and REV
- Load, FWD and REV
- Thru, FWD and REV
- Thru Match, FWD and REV

Note: The calibration calculations made by the VNWA-3E software also include forward and reverse crosstalk coupling between the transmit and receive ports, so there actually are a total of 12 calibration parameters;

however, the VNWA-3E user normally allows the software to use assumed crosstalk values rather than measured values.


Figure 6 ~ Rosenberger calibration kit consists of Short, Open, Load and Thru standards that use SMA connectors. The kit is supplied in a tin box. The Open and Thru standards are the same barrel connector shown upper-middle. The slightly different reference plane locations of the Open and Short affect the calibration so a phase delay is manually entered into the software configuration to compensate. The Short (upper-left) and Load (upper-right) components are mechanically similar and have been color-coded for easy identification (red for the short and blue for the load). Image © 2016 W. Reeve

For the measurements in this paper I calibrated over the full VNWA-3E frequency range 0.1 to 1300 MHz using 300 data points and a total sweep time of 30 s. Afterwards, I saved the calibration data as a Master Calibration File and used it for all measurements. It was determined experimentally a few years ago that a relatively small number of calibration points (300) coupled with a relatively long integration time (100 ms/point) is a good combination for calibrating the VNWA-3E. Full calibration of the VNWA-3E requires around 7 or 8 min, which includes the sweep time for each calibration standard plus the time to remove and replace them.

The measurements were made over a reduced frequency range but also using 300 data points, so the measurement sweeps had higher frequency resolution than the calibration sweeps. However, the measurement accuracy is limited by the software interpolation during measurement, so even higher measurement frequency resolution often can be used to increase accuracy where data values change rapidly with frequency. This is apparent when examining the measurements of the filters and is discussed later.

## 4. Filter description

As an example of filter measurements in this paper, I use the model MW-11200-54 bandpass filters. These were manufactured by American Electronic Laboratories (AEL) probably in the 1980s or 1990s prior to the company disappearing as the results of acquisitions. The filter's past applications are unknown, but AEL was well-known for manufacturing countermeasures and radar-warning receiver systems {AEL}. I obtained these and other used AEL filters from a surplus equipment dealer in Israel.

The MW-11200-54 is a lumped element filter composed of seventeen toroidal inductors and mica capacitors mounted on a simple printed circuit board in a high-quality milled aluminum enclosure (figure 7). The filter boards are hand-built and have no adjustments. The three units measured are s/n 1141, 1144 and 1189.

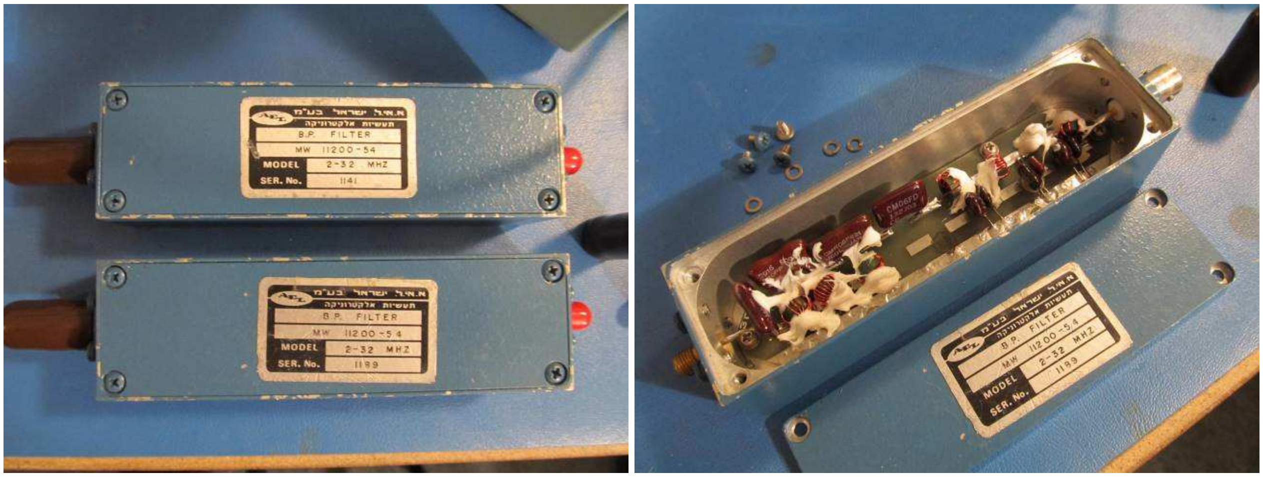



Figure 7 ~Left: Two obviously used AEL MW-11200-54 bandpass filters. Filter dimensions are 120 x 35 x 28 mm. Right: Interior view of the filter. Typical of AEL lumped element filters, parts are soldered to pads on a simple PCB and white rubbery adhesive is used to reduce microphonics and vibration effects. These high frequency filters use toroidal inductors but AEL filters for higher frequencies use single-layer air core coils. Images © 2016 W. Reeve

## 5. Filter measurements

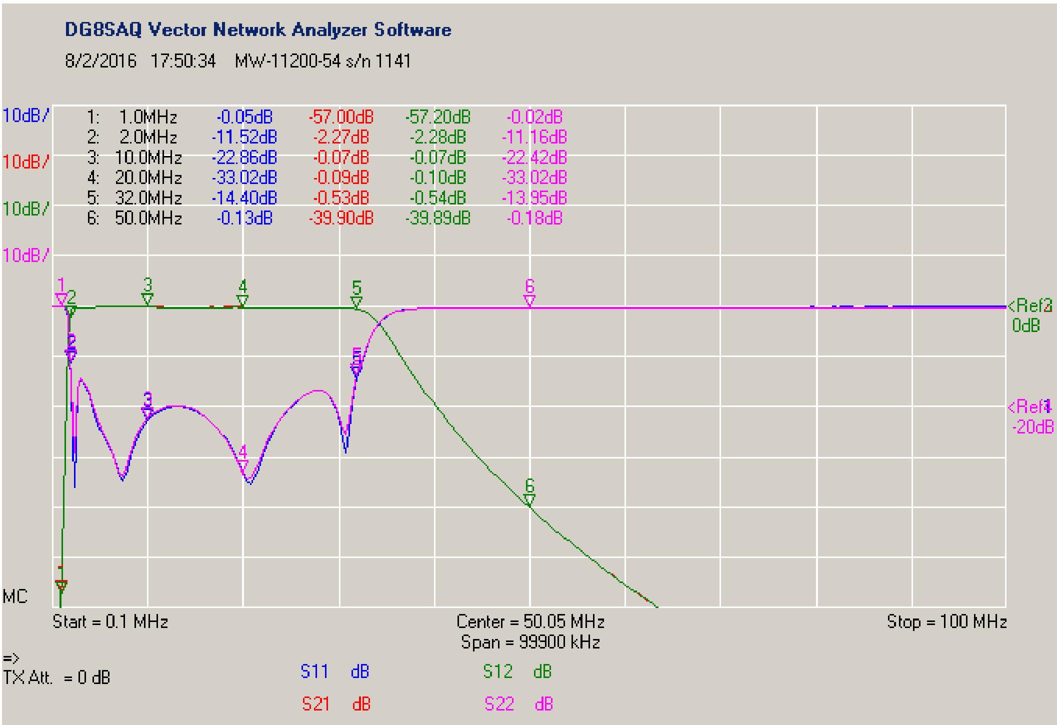
Bandpass filter characteristics usually are described by their passband response, ripple (response variation throughout the passband), impedance matching in the passband, cutoff frequencies and stopband response. The cutoff frequencies may be determined where the filter response is down by 3 or 10 dB or some other value. Since I have only a label on the filters indicating a frequency range of 2 to 32 MHz and no datasheet, I can only guess what the original requirements were for the MW-11200-54 filter. Although the basic frequency range of the filters is 2 to 32 MHz my measurements spanned 100 kHz to 100 MHz to catch their behavior outside their marked range. I looked for consistency in the measurements of the three filters to verify their performance.

One side of each filter uses a BNC-F connector and the other side uses an SMA-F connector; both connectors are 50 ohms impedance, indicating that the filter characteristic impedance is 50 ohms. My VNA test cables have SMA-M connectors so I used a BNC-F/SMA-F adapter on one end. I calibrated the VNWA-3E with the test cables but not the adapter in place (I do not have a BNC calibration standard), so the filter measurements also include any effects of the BNC adapter, which most likely is negligible at the frequencies of interest.

Each filter was measured and the results plotted in rectangular (figure 8) and Smith Chart (figure 9) forms. While the rectangular plots show all four s-parameters in dB over the 100 kHz to 100 MHz frequency range, the Smith Charts show the complex reflection coefficients and normalized impedance associated with S11 and S22 (input and output, respectively) over a narrower range of 2 to 32 MHz. In this case, the rectangular plots are easier to interpret. For presentation here, the Smith Chart grid was changed from its default colors and spacing to improve the contrast in the plot images.

Examination of the plots reveals that the filters are symmetrical, that is, the port reflection and transmission characteristics are the same for both directions (S11 = S22 and S21 = S12). The plots also reveal that the three filters are for practical purposes identical to each other. The 10 dB bandwidth is close to 35 MHz (1.7 to 36.7

MHz) while the 0.5 dB bandwidth is very close to 2 to 32 MHz. The plots use a linear frequency sweep. Later, I show the filter response with a logarithmic frequency sweep.



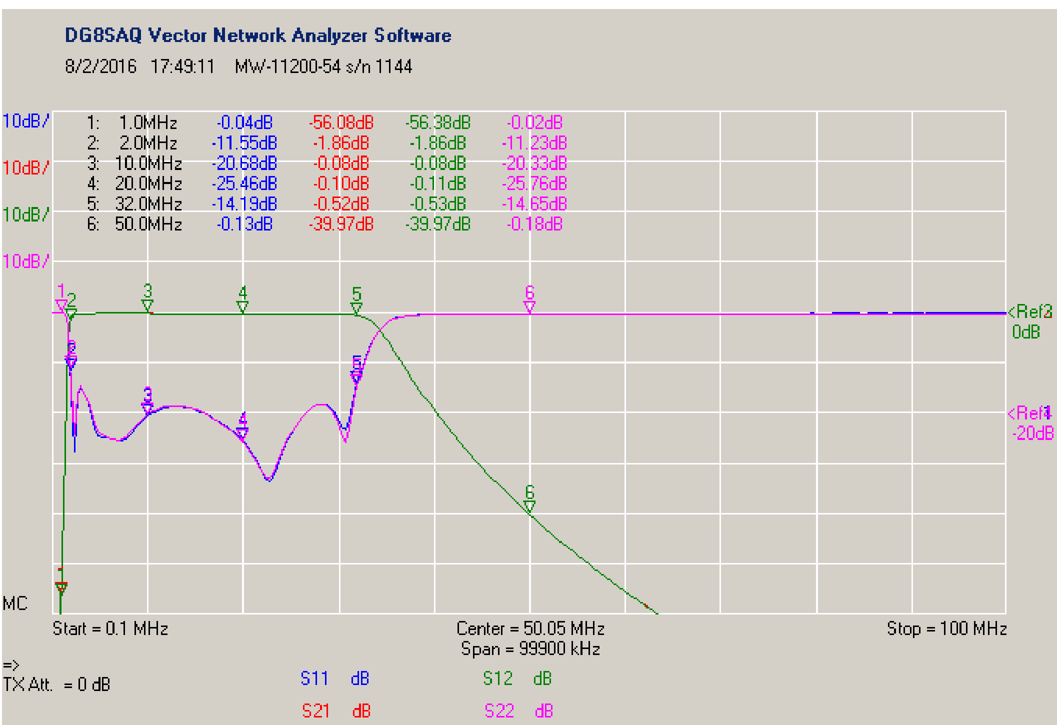
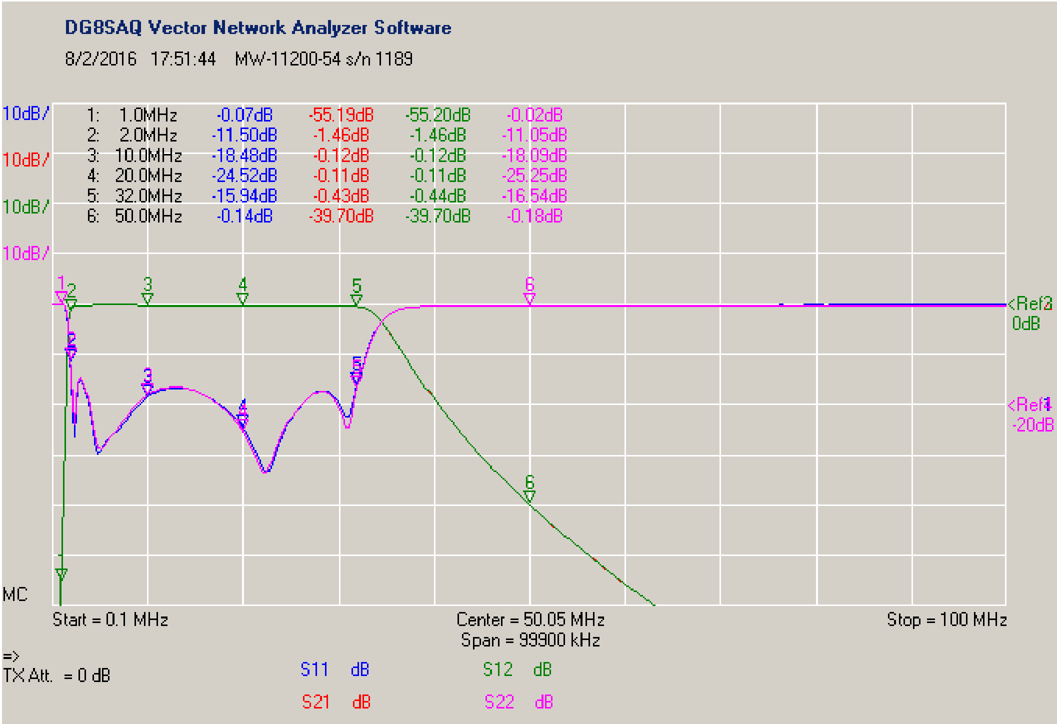




Figure 8 ~ Four s-parameters for each of three filters are plotted in a rectangular format. The parameters and associated trace colors are indicated at the bottom of the display, and corresponding marker values are shown at upper-left. The filter model and serial number is shown above the marker table.

Each vertical division is 10 dB. The reference for the S11 and S22 reflection loss traces is at the 4th division and is –20 dB. Similarly, the reference for S21 and S12 transmission traces is at the 6th division and is 0 dB.

The passband loss between approximately 2 and 32 MHz is < 0.5 dB and the reflection loss varies from 11 to 33 dB. These obviously are reflective and not absorption filters – the reflection loss outside the passband is very close to 0 dB (all incident energy is reflected instead of being absorbed and dissipated as heat).



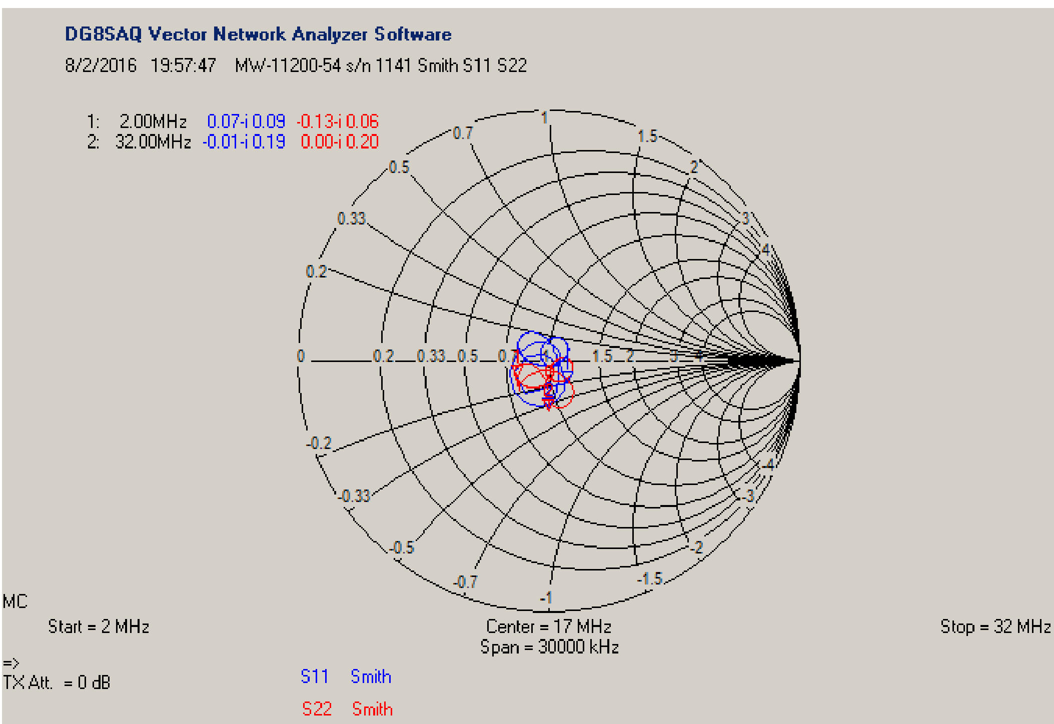
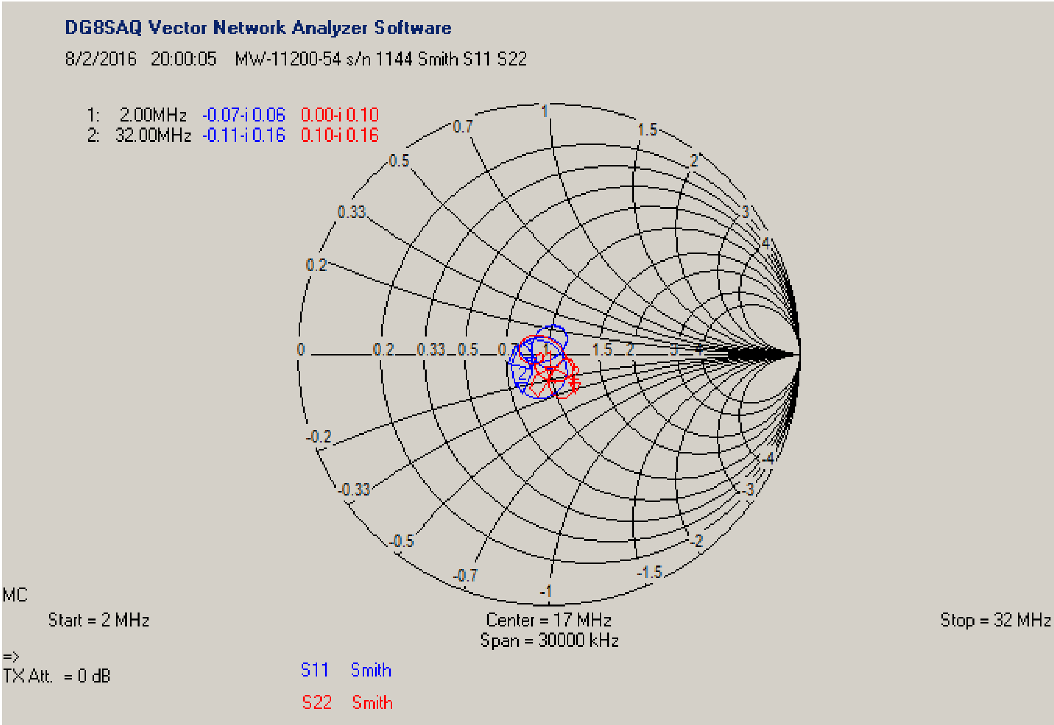
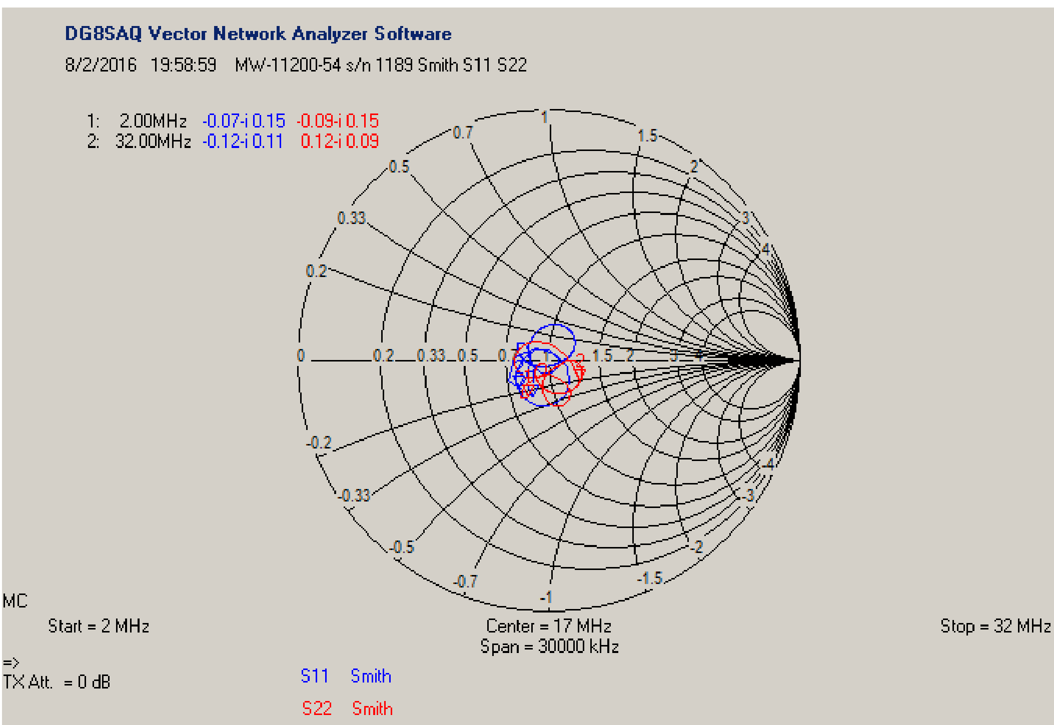




Figure 9 ~ The Smith Charts show the same information as the rectangular plots in the previous figure but only the reflection parameters S11 and S22 are shown here. Also, the frequency range has been reduced.

The start and stop frequency range is indicated on the lower sides of the chart, and the center frequency and span is shown just below the chart. The filter model and serial number is shown above the marker table.




Although the Smith Chart grid is setup to show normalized impedance, the marker tables shows the corresponding reflection loss. Because the traces are near the center of the chart, the filter is very well matched to 50 ohms over the frequency range indicated.

While the plots presented above for each of the three filters look identical, there may be subtle differences not easy to see in a side-by-side comparison. To spot any differences, the traces for a given parameter from each filter can be overlaid. For this, I made a separate set of measurements for each filter, saved the measurement in memory and then displayed all three memories on one plot (figure 10). These comparative plots show only S21 (through transmission from port 1 to port 2), and it is obvious from these and the plots for other parameters that there are no significant differences.

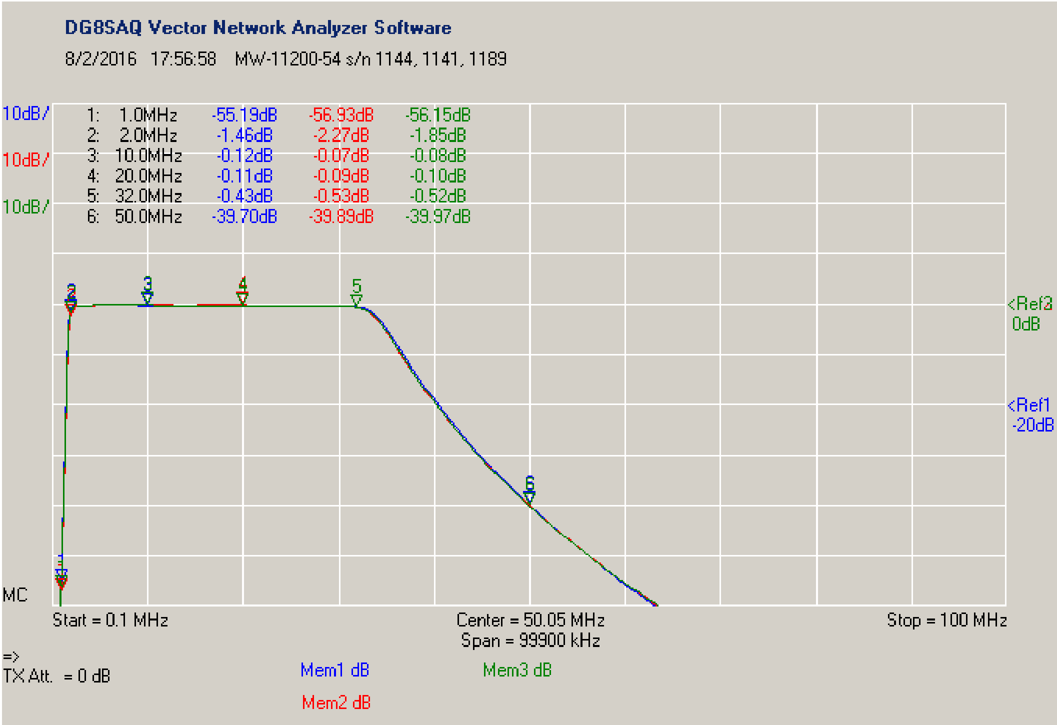



Figure 10 ~ Passband loss (S21) for the three filters overlaid on each other for comparison. This plot shows that for practical purposes the three filters have identical loss with frequency.

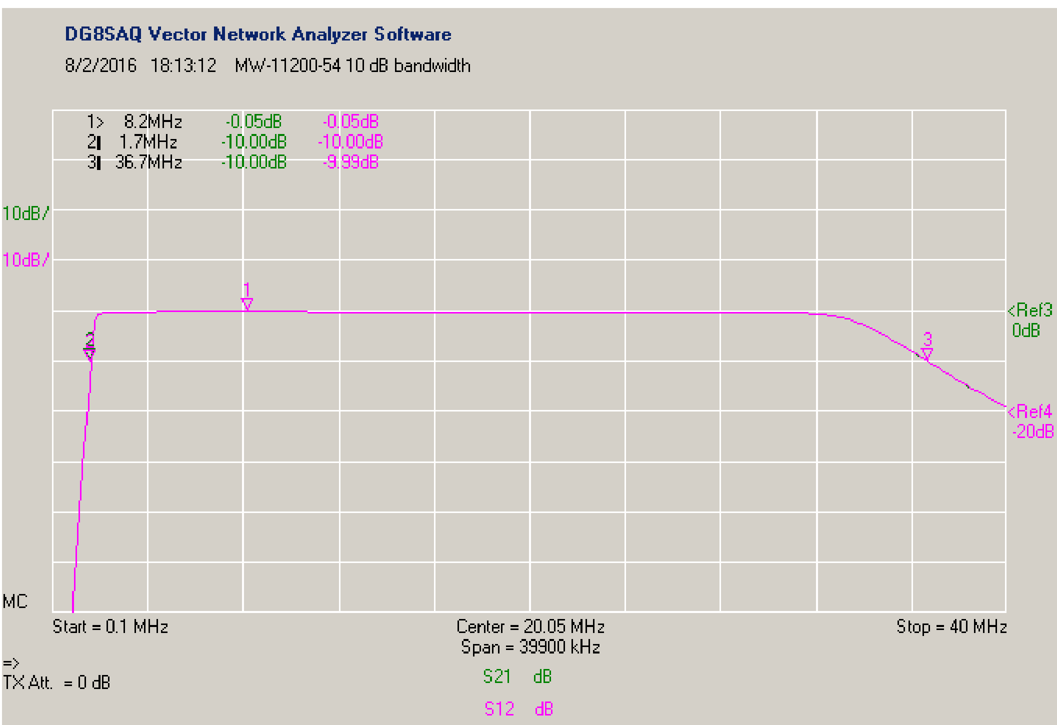



Figure 11 ~ The 10 dB bandwidth is determined by adjusting the vertical scale and then placing left and right markers (markers 2 and 3) one division below the reference (marker 1). In this case, the bandwidth is 36.7 – 1.7 MHz = 35 MHz.

To better view the passband ripple and bandwidth, I reduced the frequency sweep range to 40 MHz, thus expanding the passband trace (figure 11). The plot also may be expanded without changing the sweep range by using the software zoom function. The 10 dB bandwidth of the filter can be shown by first setting the grid to 10 dB/division and then setting the left and right markers to one division (10 dB) below the 0 dB reference. I also expanded (magnified) the vertical scale to 0.1 dB/division to allow very close examination of the passband ripple (figure 12). These measurements show the MW-11200-54 filters are very flat in the passband with only a few tenths of a dB variation.

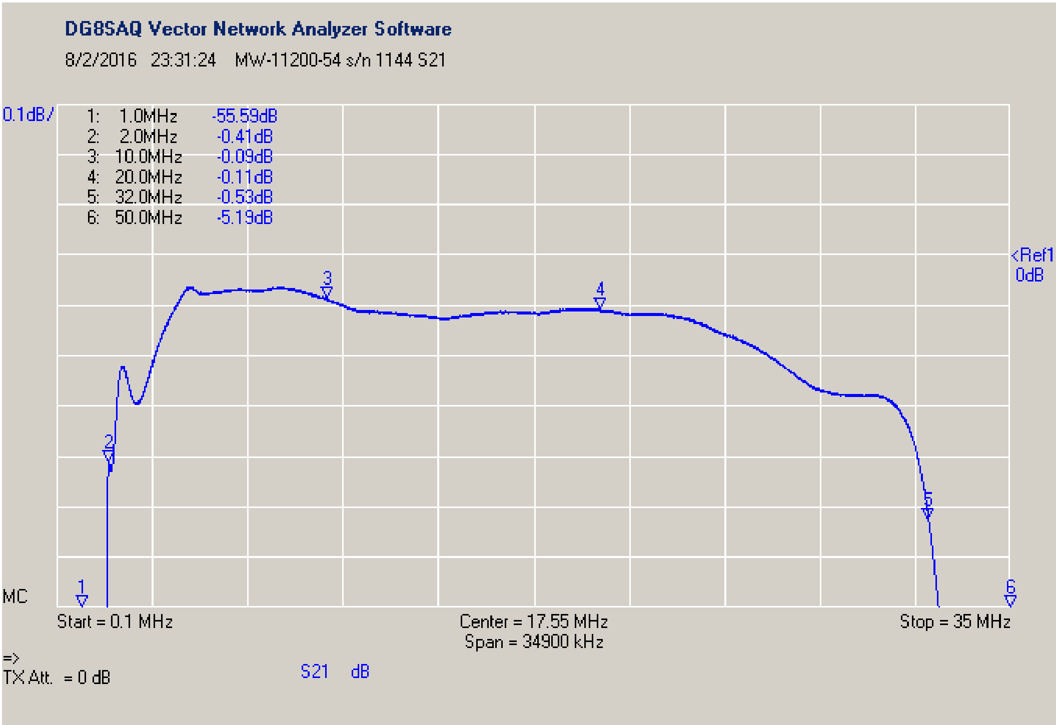



Figure 12 ~ Magnified vertical scale (0.1 dB/division) shows the passband ripple is a few tenths of a dB from 2 to 32 MHz. Although the trace is not visible at the frequencies of marker 1 and 6, valid measurements are still shown in the marker table if the measurement sweep covered the frequencies involved. Therefore, Marker 1 is valid and Marker 6 is not.

The stopband can be investigated by using sweep ranges below and above the cutoff frequencies (figure 13). The previous plots showed that stopband loss exceeds 50 dB below 1 MHz and above 50 MHz. Outside this band the losses continue to decrease, reaching 100 dB at 500 kHz and 100 MHz; however, the traces become noisy at frequencies where the VNWA-3E noise floor is reached.

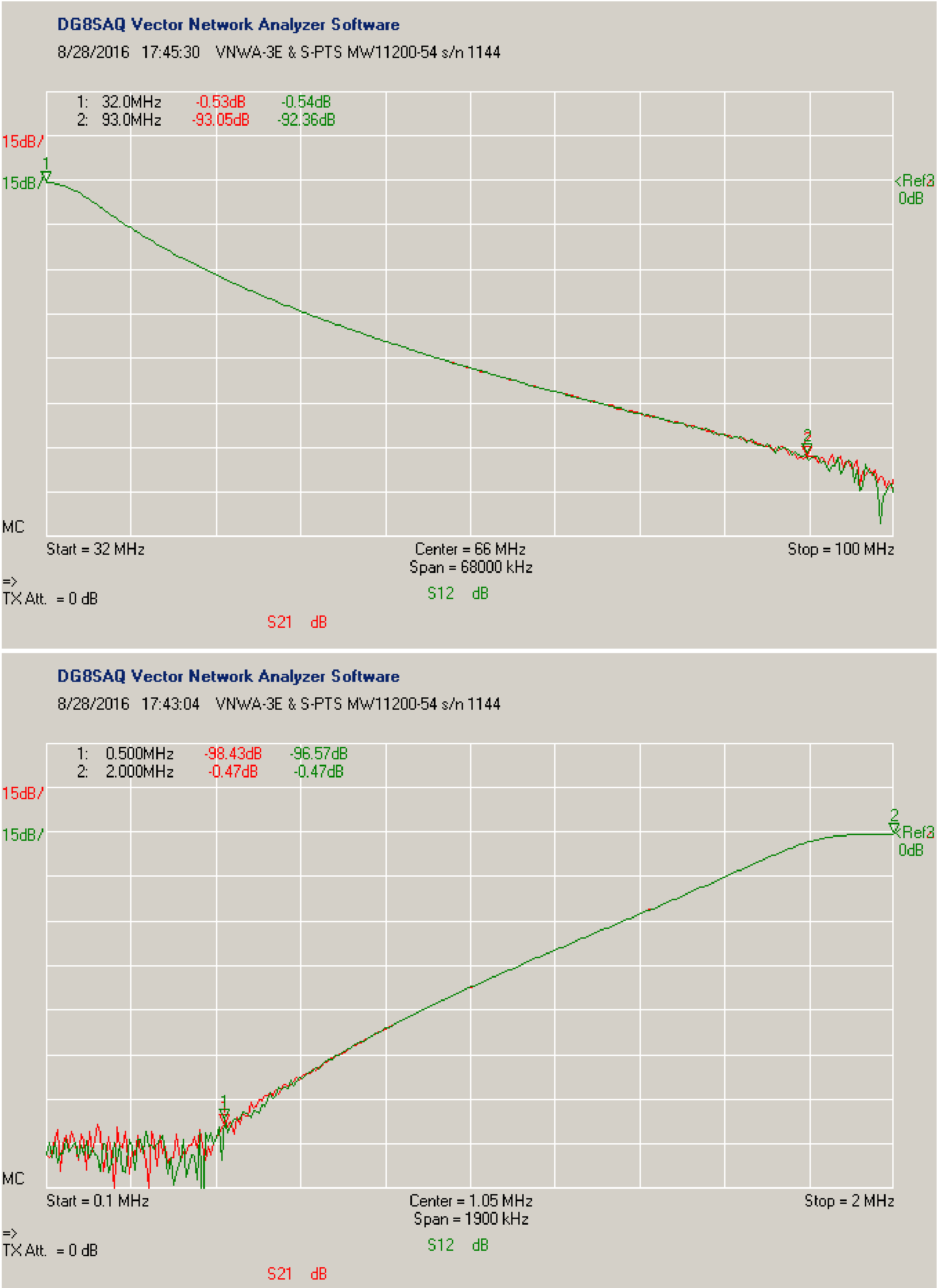



Figure 13 ~ Stopband measurements setup for 15 dB/division with 0 dB reference on the 8th grid line. Upper: Linear frequency sweep from 32 to 100 MHz shows the loss approaches 100 dB but measurements are limited by the VNWA-3E noise floor. Lower: Linear frequency sweep from 0.1 to 2 MHz indicates the stopband loss exceeds 100 dB but, as above, the measurements are limited by the instrument's noise floor.

When measurements span several decades, a logarithmic frequency sweep (figure 14) can bring out details that may be hard to discern with a linear sweep. Although the measured values should be the same for both linear and log sweeps, there may be errors where the values change rapidly in a small frequency span. This can be due to insufficient data points for accurate interpolation during measurements.

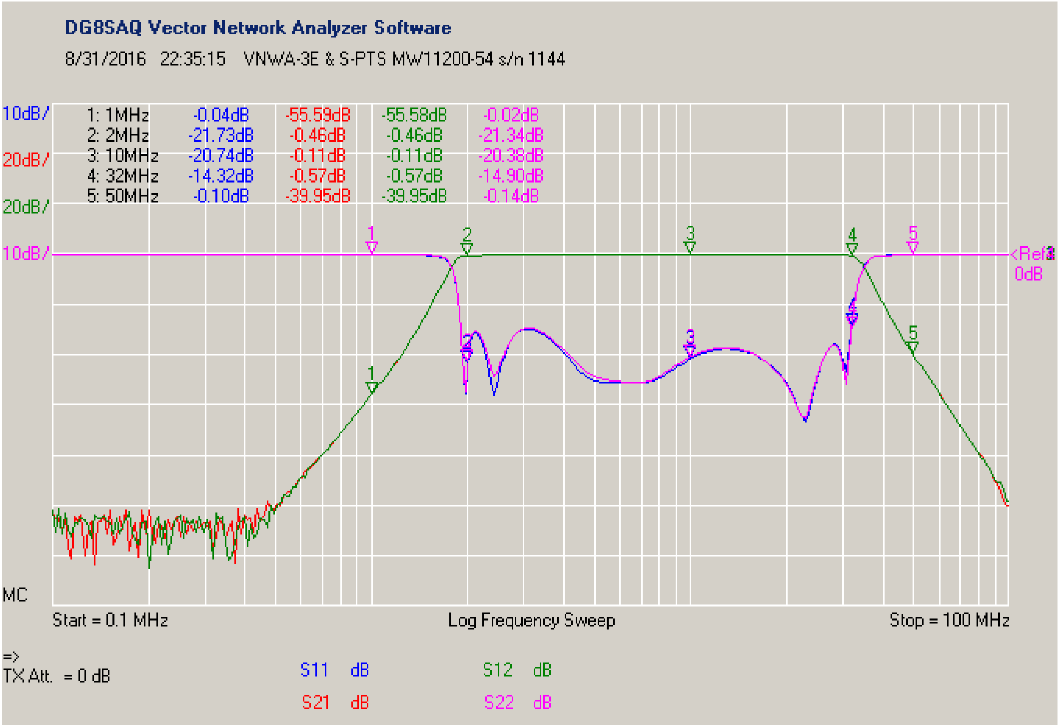



Figure 14 ~ S-parameter measurements with logarithmic frequency sweep of four decades. The range from 0.1 to 0.5 MHz is noisy because the VNWA-3E is measuring very low signal levels at its noise floor. The red and green traces are S21 and S12, respectively, and the blue and magenta traces are S11 and S22, respectively. Most points on the traces overlap. Compare S21 and S12 at 2 MHz with earlier linear sweep plots (see text).

The linear and log sweep measurements above show significantly different values for S21 and S12 at 2 MHz where the measured values abruptly change. The linear sweeps show a transmission loss of around 2 dB at 2 MHz whereas the log sweeps show about 0.5 dB. To investigate I made some comparative linear and log measurement sweeps at various frequency ranges and data points (table 1) using the same Master Calibration Files as before (300 data points from 0.1 to 1300 MHz for a frequency resolution of 4.3 MHz).

Table 1 ~ Comparison of S21 measurements at 2 MHz (filter s/n 1144)
Linear (300 and 1000 measurement points) and log (300 measurement points) frequency sweeps
0.1 to 100 MHz

| Sweep range (MHz) | S21 (dB) Linear sweep 300 points | S21 (dB) Linear Sweep 1000 points | S21 (dB) Linear Sweep 2000 points | S21 (dB) Log sweep 300 points |
|---|---|---|---|---|
| 0.1 ... 5 | 0.49 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 10 | 0.49 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 20 | 0.50 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 30 | 0.49 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 50 | 0.55 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 60 | 0.66 | 0.48 | 0.46 | 0.46 |
| 0.1 ... 70 | 0.49 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 80 | 0.48 | 0.49 | 0.47 | 0.46 |
| 0.1 ... 90 | 0.68 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 100 | 2.02 | 0.47 | 0.46 | 0.46 |
| 0.1 ... 120 | 2.88 | 0.53 | 0.47 | 0.46 |
| 0.1 ... 150 | 3.83 | 0.58 | 0.47 | 0.46 |
| 0.1 ... 200 | 4.71 | 0.63 | 0.47 | 0.46 |

It is clear the linear sweep measurements can be erroneous at 2 MHz, and the error increases with increasing sweep frequency range when only 300 and even 1000 measurement data points are used. The error can be reduced by increasing the number of data points, and thus the frequency resolution, used for measurements. It was found that at least 1000 points were required to reduce interpolation errors for the 100 MHz linear sweep range (100 kHz resolution).

Where N = number of data points in sweep and n = 0 to N–1, the frequencies used in the linear and log sweeps can be calculated from

Linear: $F_{linear,n} = F_{low} + \left(F_{high} - F_{low}\right) \cdot \left[n/(N-1)\right]$ MHz

Log: $F_{\log,n} = F_{low} \cdot \left[\left(F_{high}/F_{low}\right)^{n/(N-1)}\right]$ MHz

As expected, the linear and log sweeps produce widely different measurement frequencies as shown below for 300 data points and frequency range of 0.1 to 100 MHz:

Linear: 0.1, 0.434, 0.768, 1.102, ... , 99.332, 99.666, 100.000 MHz

Log: 0.1, 0.102, 0.105, 0.107, ... , 95.485, 97.716, 100.000 MHz

The linear sweep in this example has a constant frequency resolution of 334 kHz while the resolution of the log sweep varies from approximately 2.3 kHz at the low end to 2.3 MHz at the high end. At 2 MHz, the resolution of the log sweep is about 46 kHz, equivalent to about 2000 data points in a comparable linear sweep. The actual measurement frequencies near 2 MHz with 300 data points are

Linear: 1.771 and 2.105 Hz

Log: 1.969 and 2.015 MHz

A practical way of handling the potential problem of inadequate resolution is to examine the plot to find sharp transitions and then simply reduce the frequency range or increase the number of measurement points at the frequencies of interests and remeasure.

## 6. Measurements summary

The many filter measurements discussed in this paper are summarized (table 3).

Table 3 ~ Measurements summary for MW-11200-54 bandpass filters s/n 1141, 1144, and 11889

| Parameter | Value | Remarks |
|---|---|---|
| 0.5 dB passband | 2.0 to 32.0 MHz | |
| 10 dB passband | 1.7 to 36.7 MHz | |
| Passband ripple | +0.04, –0.3 dB | Referenced to mid-band loss |
| Passband loss | 0.5 dB maximum | Referenced to 0 dB |
| Impedance matching | > 11.5 dB return loss 2 to 32 MHz | Equivalent to 1:1.7 VSWR |
| Stopband loss | > 55 dB at < 1 MHz and > 50 MHz<br>100 dB at 500 kHz and 100 MHz | |

## 7. Conclusions

A vector network analyzer enables detailed filter measurements, demonstrated by measuring three identical AEL MW-11200-54 HF filters. The importance of using the appropriate frequency range and an adequate number of measurement points in the measurements is discussed. For the demonstration filters, it is found that the marked frequency range of 2 to 32 MHz corresponds to the 0.5 dB passband frequencies. The passband ripple is very small, amounting to a few tenths dB and the filters are well matched to 50 ohms impedance throughout their passband. The filters have sharp edges and are reflective outside the passband.

## 8. References, further reading and links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{MW101} http://www.microwaves101.com/encyclopedias/smith-chart-basics#whats

{Reeve-SPTS} http://www.reeve.com/Documents/Articles%20Papers/Reeve_S-ParamTestSet.pdf

{SSS} http://www.sss-mag.com/smith.html

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- 0.3 (Add'l cleanup, 12 Aug 2016)
- 0.4 (Minor cleanup, 18 Aug 2016)
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- 0.7 (Added log frequency plots, 01 Sep 2016)
- 0.8 (Commented log and linear measurement differences, 07 Sep 2016)
- 0.9 (Completed 1st draft, 10 Sep 2016)
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