Optimizing the Location of Stubs For Harmonic Suppression

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George, W2VJN, published a very thought-provoking article in the Jan/Feb 2015 issue of National Contest Journal on the placement of stubs for harmonic suppression in the feedlines of monoband antennas. The basic concept is solid, but I differ with him on the implementation. What we agree on is that 1) a resonant antenna that presents a load in the range of 25-100 ohms on its operating frequency will look like some very high impedance on the second harmonic; 2) the SWR at the second harmonic is typically quite high; 3) a stub will provide the greatest suppression if placed at a point along the line where the impedance is at a maximum at the frequency where suppression is desired; and 4) a stub that is poorly located along the line may provide little if any harmonic suppression.

There's another important factor – the interaction between the stub and the amplifier's output network. Modern power amplifiers create rather strong harmonics that must be filtered by a powerful output network – the second harmonic may be only 6 dB down from the fundamental, so this network must suppress the second harmonic by at least 40 dB. The effectiveness of any passive network depends upon the load impedance. With or without the stub, the transmission line can transform the antenna's impedance at the harmonic to a value that reduces the suppression provided by that network by 25 dB! When we place a stub on a line, we establish a new standing wave pattern between the stub and the amplifier. Thus, the second part of our problem is to adjust the length of the line between stub and amplifier so that the standing wave pattern optimizes the effectiveness of the output network.

A stub works to suppress a harmonic by placing a short across the line at the harmonic frequency. If we place it at a low impedance point, it provides very little suppression because we're placing a short in parallel with a short. And, if the length of coax between stub and amplifier degrades the suppression that the output network was providing, the total suppression (output network plus stub) may be no better than without the stub. Indeed, George began pursuing this problem because he was building stubs for stations owners who reported that they weren't working well.

Overview of the Process: To avoid confusion, I won't go into the details of George's suggested procedure. Read the NCJ article if you're interested. Here's what I recommend.

Step 1: Measure the complex impedance of the feedline in the shack (with the antenna connected) at the frequency of the second harmonic.

Step 2: Use N6BV's ***TLW*** software (comes with the ARRL Antenna Book), AC6LA's free ***Zplots*** Excel spreadsheet or his ***TLDetails*** windows program to find the impedance peaks on the line. Or, use AE6TY's free SimSmith software. It's a Smith Chart program that runs in Java.

Step 3: Break the line at one of those points, insert a coax Tee, and add the stub. If you want a second stub (for more attenuation), add it a quarter-wave closer (on the harmonic band) to the transmitter.

Step 4: Make the line between the stub and the output of your rig or power amp a length that preserves the harmonic suppression of the rig or the power amp.

Details of the Steps: There are several methods for each step, depending on the available measurement and software tools. Our example is a 40M dipole with a stub to suppress the second harmonic.

Step 1: If you have only a single-frequency antenna analyzer that reads complex impedance (R +/- jX), disconnect the coax from the rig, connect it to the analyzer, and measure it at the frequency of the harmonic (I chose 14.175 MHz, the middle of 20M). Note that it **is** important to enter the sign of the reactance. Some analyzers don't read the sign, providing a procedure for finding it, **but AC6LA and VK1OD have observed that it can give an erroneous result when measuring the impedance of a transmission line feeding an antenna.** See http://www.ac6la.com/zpapndx3.html and http://owenduffy.net/blog/?p=2436 If you have a vector impedance analyzer or vector network analyzer, measure the impedance over the limits of the harmonic band (in our example, 20M).

[For simple antennas like a dipole, we can model it using NEC and compute the SWR at the harmonic. Put the cursor at the center of the band and read the impedance. To make use of this data, we'll need to know the length of the line. For the measurement method above, we do not need to know the length of the line, although if we do, and if we know line loss, we can compute suppression all the way to the antenna.

Step 2 – using TLW: Chose the coax type you are using (if multiple types in the run to the antenna, choose the type of the section of the line that you measured). Enter the measured Z value, checking the ***Input*** box (because you measured at the input end of the line). Enter the measurement frequency (14.175 MHz) and the length of the line of the line if you know it. If you don't, use any length greater than a wavelength. (If your impedance is from NEC, check the ***Load*** box, and you will need to know the length of the line.) Now, go to the Graph section, select **Voltage/Current**, and click on **Graph**. This gives us a graph of voltage and current peaks. Place your choke at the location of the most convenient voltage peak. *[Caution – Don't use the NEC approach with TLW unless you know the length of the line to good accuracy and are using the same type of coax for the entire run.]*

Adding Coax – If you can't put the stub within the length of the existing line (the voltage peaks may be at inaccessible locations or it's hard line that you don't want to break), then note the location of the voltage peak closest to the transmitter and the spacing (feet and inches) between peaks (a half wave), add enough coax to extend the line to the next peak, and put the stub there. The added coax should have the same Z_O, but can have a different V_F. If the V_F is different, change to the new coax type in TLW, select the ***Load*** box, Click on ***Graph***, and read the distance to the next voltage peak. (This last step is important – TLW won't redraw the graph automatically, so without clicking on ***Graph*** you'll be looking at the earlier version of the problem.

Step 2 – using TLDetails Download from ac6la.com. Set the line type, enter the frequency, enter the measured R and (signed) X at the station end of the line, choose "At Input". Set the initial line length to 0. Use the length spin button to increase the length until the blue dot (the "At Load" marker) is at the right side of the Smith chart. That's the length toward the antenna from the station end of the line where the first stub should be placed. Follow the same procedure as with TLW if you want to add coax before the stub.

Step 2 – using *Zplots*: Download spreadsheet from ac6la.com, load into Excel (does not run in other spreadsheet programs), see the instructions at http://ac6la.com/zplots1.html#GenerateFF to ***Generate Data for a Transmission Line at fixed frequency***.

Step 2 – using *SimSmith*: If your measurement is a single data point, enter it in the ***Load*** block, and set SimSmith to that frequency. If you have made a sweep measurement, export the data from your measuring instrument in Touchstone format (it's a plain text file with an s1p extension), and import it into SimSmith as a "Load File." *[SimSmith author AE6TY advises that the only form of s1p file that older versions of SimSmith imports is the "S" format. Version 11.5 and later will also accept "Z" format.]* Be sure to set the SimSmith generator frequency to the center of the measured sweep data. Add a transmission line to the model and choose the coax type you're using. Looking at the Smith Chart display, vary the length of the transmission line you just added until the antenna (or the single data point) is centered along the horizontal line at the right side of the chart. This is a high impedance point on the line, it repeats every $\lambda/2$, and we want to put our stub at one of those points. A negative length in SimSmith moves along the line toward the antenna (we must break the feedline at that point and insert the stub), a positive number moves away from the antenna (we must add coax to the line and put the stub there). As with TLW, if we add coax to the system, we must add coax with the same same Z_O, but it can have a different V_F. If it does, change the coax in the model to match what you're using.

Step 3 – Building and installing the stub: Install a connector on one end of a piece of coax, cutting the coax about 10% longer than the computed value. Strip ½-in or so at the far end, short the shield to the center conductor. Connect the stub to an impedance measuring device, and vary the frequency until you see an impedance near zero ohms with X also near zero ohms. It should be below your desired frequency by about 10%. Use the actual percentage below your target frequency to tell you how much to cut, and cut about half that much. Repeat until the stub is at the desired frequency. Carefully solder the shorted end and weatherproof it. Add a coax Tee to the line where the stub will go. Connect the antenna side of the feedline to one side of the Tee. Using a coax barrel, connect the transmitter side to the male connector, and connect the stub to the other side of the Tee.

In general, it's best to add the stub in the existing length of line without making the line longer – the longer line will increase the loss slightly. Stubs are also effective at impedance peaks near the antenna, so if that is convenient, consider it. We may also want to add a second stub – see below – so that's another good reason for putting the first stub closer to the antenna.

Step 3a – Placing a Second Stub: Building the stub from high quality coax like Belden 8237, 8238, 8213, or Times LMR400 should provide about 30 dB of suppression at the second harmonic. We can get an additional 30 dB of attenuation by adding a second stub. Our first stub disturbs the line by placing a short across the line on 20M, so it changes the 20M standing wave pattern between it and the transmitter. Because impedance minima and maxima are 90 degrees apart, our next maxima will be 90 degrees closer to the transmitter (at the harmonic frequency). Think about this when deciding where to put the first stub – depending on how much of the line you have access to, you may be able to locate both stubs so that you don't have to make the line longer.

Alternate Methods: There are, of course, alternate methods for measuring feedline Z and finding voltage maxima. Use the methods that work for you, and with the resources available to you. SimSmith has the added advantage of allowing us to compute the attenuation of the stub over the range of frequencies where we measured Z. It can also compute the attenuation of a second stub. To do that, we must know the feedline length and its attenuation, subtract it from our measured data (negative feedline length), then add back in the same feedline to the stub (and the second stub if we use it).

T**he Usefulness of Two Stubs When We Can't Easily Find the High Voltage Point:** Sometimes it isn't practical to find the high voltage point. The effectiveness of the stub nearest the antenna will depend on luck – anything from a few dB to 36 dB (because we haven't found the null). But the second stub <u>will</u> be good for 30 dB, because we <u>know</u> it's 90 degrees from a short (the first stub)!

Know Your Coax: Sometimes we splice runs of coax together to reach the antenna, and they may not all be the same type. We might use hard line for the long run to a tower, with a good RG8 from the end of the hard line to the shack. We need to know the type(s) of the coax only within the section of the run between where we make our measurement and where we place the stub, and between the stub and the amplifier. For good accuracy, we need good data for the coax for that part of the run. Other coax in the run to the antenna contributes to establishing the locations of the nulls, but we don't need to know about it except to compute loss (including attenuation at the harmonic). Note also that if we are adding coax to insert the stub, we don't care about the run to the antenna, only the coax we're adding and between the stub and the amplifier output.

Step 4 Discussion – Amplifier Output Networks In vacuum tube amplifiers, these networks function both as very good low pass filters and as impedance matching networks. Two common filter configurations are in common use. Looking at the schematic starting from the tube or transistors, the ***pi-network*** (named that because it resembles the Greek letter ***π****),* has *a* shunt capacitor, followed by a series inductor, and another shunt capacitor. The second common network in vacuum tube amplifiers is the ***pi-L***, which starts with a pi-section and is followed by a second series inductor. Solid state amps, which use output devices having relatively low output impedance, often utilize multi-stage eliptical filters, with shunt C as the last element, and may do little or no impedance matching. Pi networks and elliptical filters provide the greatest attenuation into loads of 50 ohms or greater; pi-L networks work best into loads of 50 ohms or less. Since our stub causes line impedance (at the second harmonic) to vary from a near short to a near open every 90 degrees, we can give the amp its optimum load at the second harmonic simply by using the right line length between the stub and the amplifier. k9yc.com/Coax-Stubs.pdf includes a table listing the output network configurations of many popular power amplifiers. Consult the manual for amplifiers not listed.

Step 4 – Optimizing Line Length Between Amp Output and the Stub: Luckily, we don't need to be very precise about the length of this line – getting within about 35 degrees of optimum loses only about 1 dB of harmonic suppression, 45 degrees only about 3 dB. If we knew the actual values of L and C in the amplifier's output network, we could model it in TLW or SimSmith and get very precise, but that information is rarely available. We can get reasonably close (within that +/- 45 degree range of ideal) by using this rule.

- ***If the last element (nearest the output terminal) is a series inductor, make the coax between the amp and the stub as short as possible or some even multiple of half wavelengths at the harmonic.***
- ***If the last output component is a capacitor, make the coax to the stub some odd number (1, 3, 5, etc.) of quarter wavelengths at the harmonic.***

If using two stubs, the coax length we're discussing here is that from the power amp to the first stub it sees.

Note that this rule does not yield optimum results for all cases, because that output network may be adjustable to match our particular antenna at the operating frequency. But it does get us "in the ballpark" for most antennas that are reasonably well matched, and that's likely to be close enough that we don't lose much of the harmonic suppression of the output stage. Most multi-transmitter stations have multiple coax jumpers connecting relay boxes or patch panels that switch antennas to amplifier outputs, usually with wattmeters inline. Before optimizing line length between stub and amplifier, I had nearly a wavelength between my 20M stub (outside the shack, coiled above my entry panel) and my Titan amplifiers.

As an experiment, I inserted a voltage probe at the output of my Ten Tec Titan (pi-L) and Elecraft KPA500 (elliptical filter) and measured 2nd harmonic suppression as I varied the length line to the first stub, and compared it to a 50 ohm dummy load. For both amplifiers, following the rule of thumb resulted in suppression that was at least as good as into the dummy load, and both worst case and best case suppression occurred 10- 30 degrees one side or the other from the rule of thumb.

Going Beyond the Second Harmonic

Optimizing stubs for harmonics other than the second If a stub is intended to suppress the third harmonic rather than the second, our design and measurement should be at that third harmonic frequency. Likewise, if the stub is intended to suppress the fourth harmonic as well as the second, we should measure and attempt to optimize at both harmonics.

Optimizing for more than one harmonic Consider, for example, the stub for our 40M antenna – although 20M is usually most critical, we usually would like it to also suppress the 4th harmonic on 10M. The impedance at the antenna is likely to be fairly high on 10M, but the phase, and thus the position along the line of the impedance peaks may be different, and V_F will be slightly higher. If we have optimized the placement of the stub for 20M, we have a good chance of being "in the ballpark" but not necessarily optimum on 10M. The good news is that we usually need a lot less suppression on higher order harmonics.

What if we're using two stubs to increase suppression on 20M? We placed them 90 degrees apart on 20M, which makes them 180 degrees apart on 10M, and makes the second stub relatively ineffective. Shifting its position by only 20^O on 20M would sacrifice a few dB of attenuation on 20M, but would greatly improve attenuation on 10M. Whether to do this depends entirely on how much attenuation is needed on the two bands in question.

We still must consider the length of line between the stub and the power amp. What was "good" for 20M could turn out to be "poor" for 10M. The same tactic of adding or subtracting 20^O or so of line on 20M would sacrifice a few dB of attenuation on 20M but significantly improve attenuation on 10M.

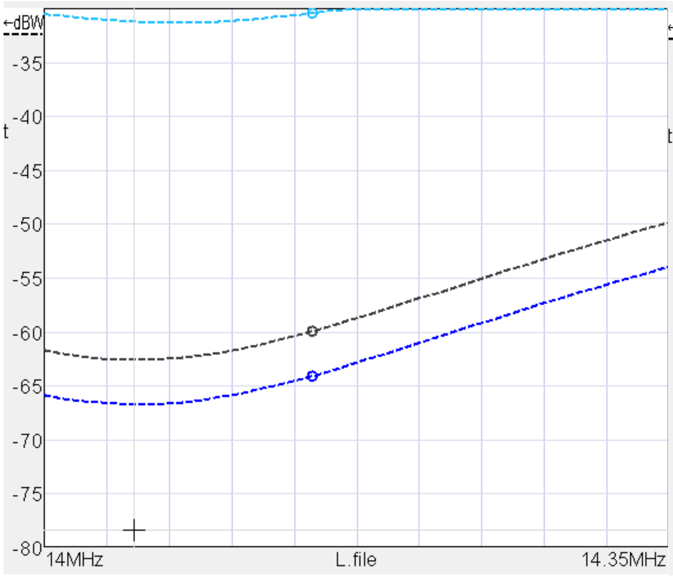
Modeled Results For Two-Stub Filters

How much harmonic suppression can we get from a well-placed pair of stubs? The top pair of graphs on the following page compare the response, modeled in SimSmith, for our 40M dipole with stubs made from

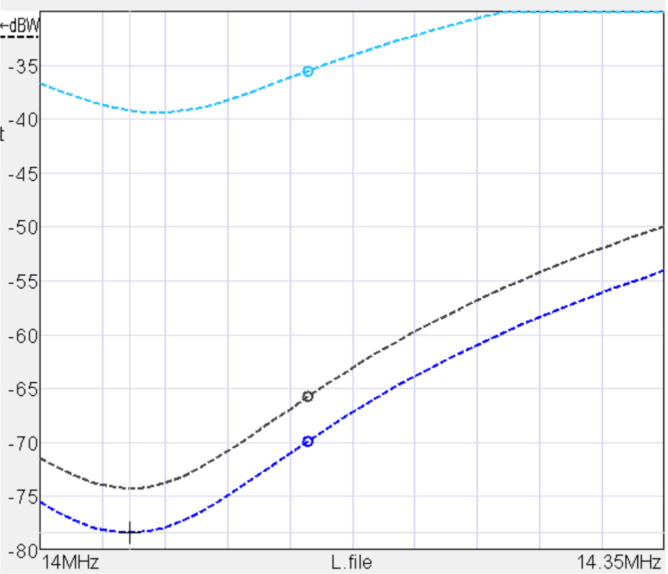
RG8X and stubs made with RG8. On all three plots, the upper curve is the attenuation between the amplifier and the nearest stub, the next curve is the total attenuation to the second stub, and the lower curve is the total attenuation to the antenna. These stubs are tuned for maximum attenuation in the CW part of the band, because harmonics of the most of the 40M phone band lie outside the 20M phone band.

Note that the RG8X stubs have less attenuation but a flatter response. This is because the smaller coax has more resistance, is a less ideal short circuit, thus lower Q. The model assumes that the spacing between the amplifier and the nearest stub has been adjusted so that it not degrade harmonic suppression in the output stage. The line is 100 ft long, and the loss in the line at the second harmonic without the stubs is 9.1 dB (because of the severe mismatch at the harmonic).

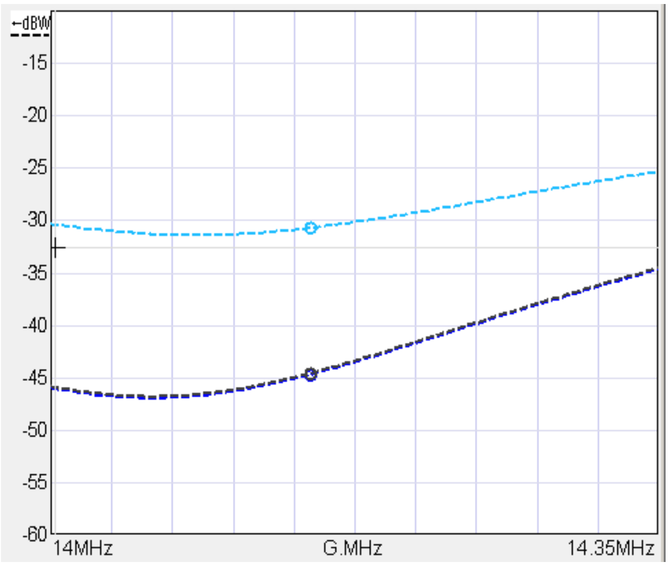
The lower graphs make the same comparison for an antenna that is resonant on both 40M and 20M. The stubs provide a bit less attenuation (the line is matched at the second harmonic, so there is no impedance peak), and because the loss in the line at the second harmonic without the stubs is only 0.65 dB (no loss due to mismatch).



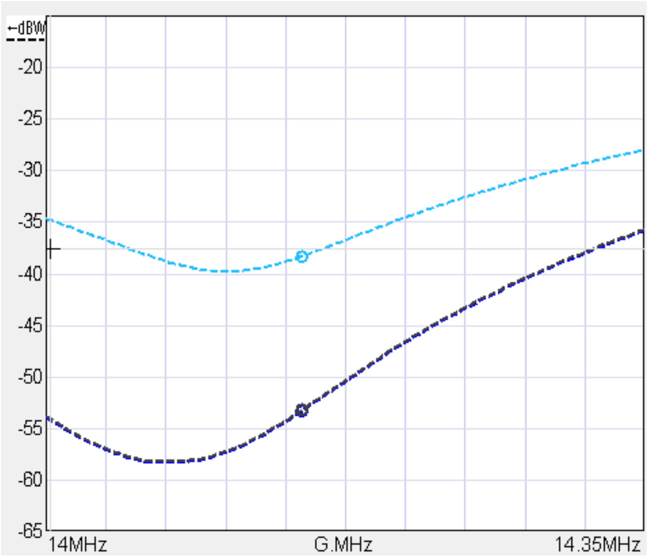
Two RG8X Stubs on 40M Dipole



Two RG8 Stubs on 40M Dipole



Two RG8X Stubs When 20M is 50 Ohms



Two RG8 Stubs When 20M is 50 Ohms

Optimizing the Position of a Receive Stub

Working The Problem In Reverse – In receive mode, the antenna is the source and the receiver input is the load. Receive stubs are usually working at the fundamental frequency of the harmonically related band below where we're operating, and are designed to prevent that transmitter from overloading our receiver. Just as the output impedance of an amplifier will vary with frequency, so can the input impedance of a receiver's input stage. To place this stub, we disconnect the antenna from the receiver and measure the impedance of the receiver input at that lower frequency. Sticking with our 40M dipole example, the process becomes:

Step 1 – Measure the receiver input impedance, either at the receiver input, or at the end of a length of coax connected to it.

Step 2 – Enter the measured impedance in ***TLW, TLD, ZPlots***, or ***SimSmith*** as the ***Load***, make the line length at least a half wave on the lower band (in our example, 80M), and ***Graph*** the Voltage/Current standing waves. In SimSmith, coax going toward the antenna should be entered as negative length (because the antenna is now the ***Source***, and the receiver is the ***Load***).

Step 3 – As before, find a convenient voltage maxima in ***TLW, TLD, or ZPlots***, or a point near the right end of the horizontal line through the center of the Smith Chart in ***SimSmith***. This optimizes the stub location with respect to the receiver input.

When placing a receiving stub, be careful not to change the position of any stubs already inserted for harmonic suppression.

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