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Optimizing the Location of Stubs for Harmonic Suppression

George Cutsogeorge, W2VJN, earlier this year submitted a very thought-provoking article (see "Optimizing the Performance of Harmonic Attenuation Stubs," January/February 2015 *NCJ*) on the placement of stubs for harmonic suppression in the feed lines of monoband antennas. The basic concept is solid, but I differ with him on the implementation. What we agree on is 1) a resonant antenna that presents a load in the range of 25 Ω to 100 Ω on its operating frequency will look like a 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: Interaction between the stub and the amplifier's output network. Modern power amplifiers generate 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 that network provides 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. Placing it at a low-impedance point provides very little suppression, because we're placing a short in parallel with a short. If the length of coax between stub and amplifier degrades the suppression that the output network was providing, the total suppression (output network + stub) may be no better than it would be 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.

Process Overview

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:

1. Measure the complex impedance of the feed line in the shack (with the antenna connected) at the frequency of the second harmonic.
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.
3. Break the line at one of those peaks, insert a coax T, and add the stub. If you want a second stub (for greater attenuation), add it 0.25 λ closer (on the harmonic band) to the transmitter.
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.

The Details

There are several methods for each step, depending on the available measurement and software tools. Our example is a 40 meter 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 (choose 14.175 MHz, the middle of 20 meters). 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[1] and VK1OD[2] have observed that it can give an erroneous result when measuring the impedance of a transmission line feeding an antenna. If you have a vector impedance analyzer or vector network analyzer, measure the impedance over the limits of the harmonic band (20 meters in our example).

For a simple antenna such as a dipole, you 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, you must know the length of the line. For the measurement method above, you do *not* need to know the length of the line, although if you do, and if you know line loss, you can compute suppression all the way to the antenna.

Step 2 — Using *TLW*: Choose the type of coax you are using (if multiple types are in the run to the antenna, choose the type of the section of the line that you measured). Enter the measured impedance 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 1 λ. (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 you are using the same type of coax for the entire run.*

If you can't put the stub within the length of the existing line (the voltage peaks may be at inaccessible locations), then note the location of the voltage peak closest to the transmitter and the spacing (feet and inches) between peaks (0.5 λ), add enough coax to extend the line to the next peak, and put the stub there. The added coax should have the same impedance but can have a different velocity factor (VF). If the VF 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 the software from **http://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 the software from **http://ac6la.com** and load it into *Excel* (it will 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. If you have made a sweep measurement, export the data from your measuring instrument in Touchstone format (it's a plain text file with a .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.)

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 0.5 λ. Place your stub at one of them. A negative length in *SimSmith* moves along the line toward the antenna (you must break the feed line at that point and insert the stub), a positive number moves away from the antenna (add coax to the line, and put the stub there).

As with *TLW*, if you add coax to the system, you must add coax of the same impedance, but it can have a different VF. 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 percent longer than the computed value. Strip one-half inch or so at the far end, and 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 0 Ω with X also near 0 Ω. It should be below your desired frequency by about 10 percent. Use the actual percentage below your target frequency to tell you how much to cut, and cut about one-half as much. Repeat until the stub is at the desired frequency. Carefully solder the shorted end and weatherproof it. Add a coax T to the line where the stub will go. Connect the antenna side of the feed line to one side of the T. Using a coax barrel, connect the transmitter side to the male connector, and connect the stub to the other side of the T.

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 peaks near the antenna, so if that is convenient, consider it. You may also want to add a second stub (see below), which is 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, such as Belden 8237, 8238, 8213, or Times LMR400, should provide about 30 dB of suppression at the second harmonic. Another 30 dB of attenuation is possible by adding a second stub. The first stub disturbs the line by placing a short across it on 20 meters, so it changes the 20 meter standing wave pattern between it and the transmitter. Because impedance minima and maxima are 90° apart, the next maximum will be 90° closer to the transmitter. Consider 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 position *both* stubs without making the line longer.

There are, of course, alternative methods for measuring feed-line impedance 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 you to compute the attenuation of the stub over the range of frequencies where you measured Z. It can also compute the attenuation of a second stub. To do that, you must know the feed-line length and its attenuation, subtract it from your measured data (negative feed line length), then add back the same feed line to the stub (and the second stub, if used).

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 decibels to as much as 36 dB (because we haven't found the null). But the second stub *will* be good for 30 dB, because we *know* it's 90° from a short (the first stub).

Make sure you 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 RG-8 from the end of the hard line to the shack. You need to know the type(s) of coax only within the section of the run between where you take your measurement and where you place the stub, and between the stub and the amplifier. For good accuracy, you need good data on 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 you don't need to know about it except to compute loss (including attenuation at the harmonic).

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 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 followed by a second series inductor. Solid state amps, which use output devices having relatively low output impedance, often utilize multi-stage elliptical 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 Ω or greater; pi-L networks work best into loads of 50 Ω or less. Since our stub causes line impedance (at the second harmonic) to vary from a near short to a near open every 90°, it's possible to give the amp its optimum load simply by using the right line length between the stub and the amplifier. "Some Q&A About Coax and Stubs for Your HF Station" at **http://k9yc.com/Coax-Stubs.pdf** includes a table listing the output network configurations of many popular power amplifiers.

Step 4 — Optimizing Line Length Between Amp Output and Stub: You don't need to be very precise about the length of this line; getting within about 35° of optimum loses only about 1 dB of harmonic suppression, 45° only about 3 dB. If we knew the actual values of L and C in the amplifier's output network, it's possible to model it in *TLW* or *SimSmith* and get very precise, but that information is rarely available. You can get reasonably close (within that ±45° 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 0.5 λ at the harmonic.
- ♦ If the last output component is a capacitor, make the coax to the stub some odd multiple of 0.25 λ at the harmonic. If using *two* stubs, the coax length 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 your particular antenna at the operating frequency. But it does get you in the ballpark for most reasonably well-matched antennas, and that's likely to be close enough that you won't lose much of the harmonic suppression of the output stage.

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

Going Beyond the Second Harmonic

If a stub is intended to suppress the *third* harmonic rather than the second, 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, measure and attempt to optimize at *both* harmonics.

How about optimizing for more than one harmonic? Consider, for example, the stub for our 40 meter antenna. Although 20 meters is usually the most critical, we usually would like it also to suppress the 4th harmonic on 10 meters. The impedance at the antenna is likely to be fairly high on 10 meters, but the phase, and, thus, the posi-

Modeled Results For Two-Stub Filters

How much harmonic suppression can we get from a well-placed pair of stubs? Figures 1 and 2 were modeled in *SimSmith* for a 40 meter dipole with stubs made from RG-8X and stubs made with RG-8, respectively. 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 band segment, because most 40 meter phone segment harmonics fall outside the 20 meter phone band.

Note that the RG-8X stubs offer less attenuation but flatter response. This is because the smaller-diameter coax has more resistance, is a less-ideal short circuit, and thus has a lower Q. The model assumes that the spacing between the amplifier and the nearest stub has been adjusted so that it does not degrade harmonic suppression in the output stage. The line is 100 feet 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 40 and 20 meters. 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 to mismatch).

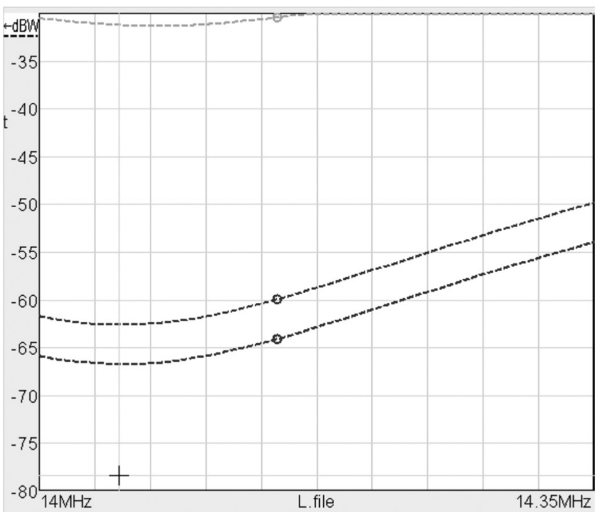

Figure 1 — Two RG-8X stubs on a 40 meter dipole.

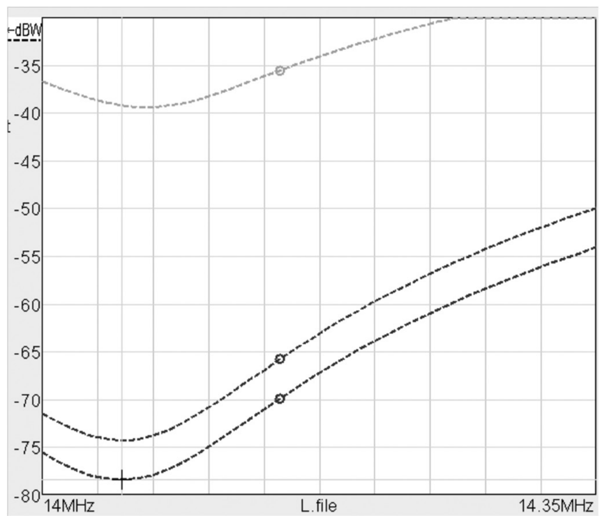

Figure 2 — Two RG-8 stubs on a 40 meter dipole.

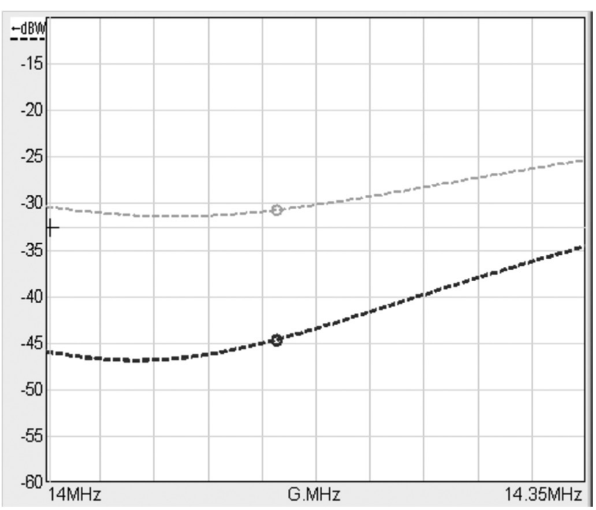

Figure 3 — Two RG-8X stubs when 20 meters is 50 Ω.

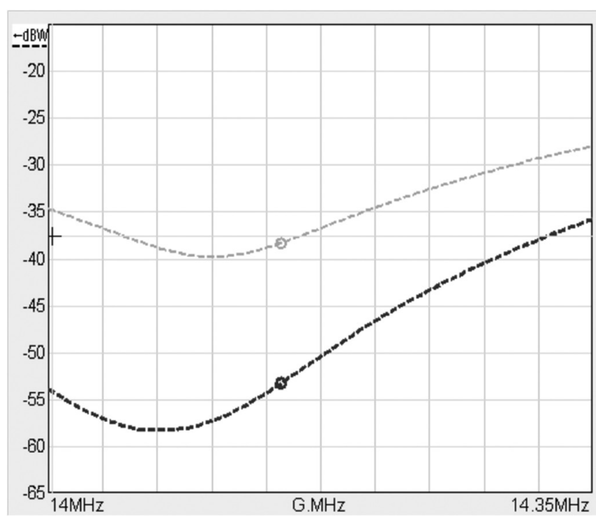

Figure 4 — Two RG-8 stubs when 20 meters is 50 Ω.

tion along the line of the impedance peaks may be different, and the VF will be slightly higher. With optimal placement of the stub for 20 meters, there is a good chance of being in the ballpark, but not necessarily optimum, on 10 meters. The good news is that you'll usually need a lot less suppression on higher-order harmonics.

What if we're using two stubs to increase suppression on 20 meters? We placed these 90° apart on 20 meters, which makes them 180° apart on 10 meters, and makes the second stub relatively ineffective. Shifting its position by only 20° on 20 meters would sacrifice a few decibels of attenuation on 20 meters while greatly improving attenuation on 10 meters. 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 worked on 20 meters could turn out to be poor for 10 meters. The same tactic of adding or subtracting 20° or so of line on 20 meters would sacrifice a few decibels of attenuation on 20 meters but significantly improve attenuation on 10 meters.

Optimizing the Position of a Receive Stub

In receive mode, the antenna is the source, and the receiver input is the load. Receive stubs typically operate at the fundamental frequency of the harmonically related band below where we're operating. These are designed to prevent that transmitter from overloading the 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, disconnect the antenna from the receiver and measure the impedance of the receiver input at that lower frequency. Sticking with our 40 meter dipole example, the process becomes:

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

2. Enter the measured impedance in *TLW, TLD, ZPlots*, or *SimSmith* as the *Load*, make the line length at least 0.5 λ on the lower band (80 meters in our example), 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*.

3. As before, find a convenient voltage maximum 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.

Acknowledgements

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Notes

[1]**www.ac6la.com/zpapndx3.html**
[2]**http://owenduffy.net/blog/?p-2436**