Demystifying the Smith Chart or *How to train your antenna*

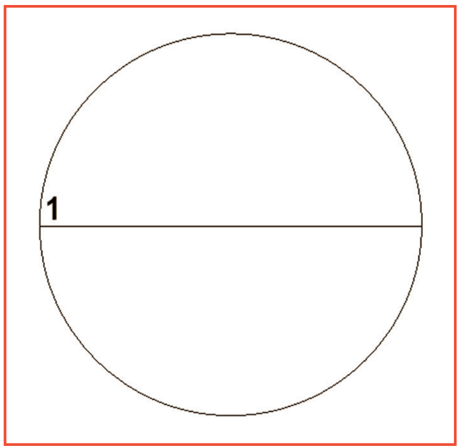

FIGURE 1: Beginning the chart. Your circle should be 1 *foj* in diameter (see text).

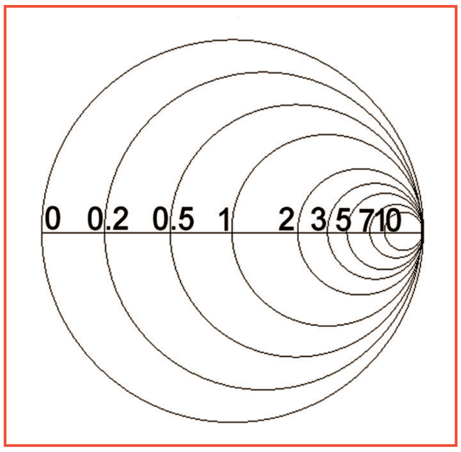

FIGURE 2: Resistance circles.

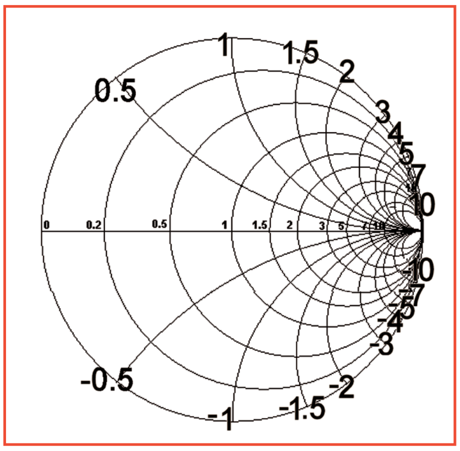

FIGURE 3: Reactance circles added.

First things first

Please be familiar with antenna impedance Z = R +j X (or at least its resistance R and reactance X, and the meaning of transmission line impedance Zo). Since Smith Charts are used with transmission lines of any impedance, they use normalised ratios, r = R/Zo, x =X/Zo, and z = Z/Zo. Note also your objective: to get the antenna impedance equal to Zo.

Suppose you've run 50Ω coax from your rig to an antenna. You soon notice the antenna's SWR – actually, the SWR on the coax. It ought to be 1:1, but, if it's too high, your transmitter may not reach full power output. What to do? What do to? And – how? The *how* of it is easy to understand and do with special graph paper called a *Smith Chart* [1]. So, let's draw one, using the 'doodling' skills we learned back in primary school.

How to draw the chart

The Smith Chart is based on a sequence of overlapping circles.

Part 1: Resistance circles, r

Put a standard sheet of paper on the table. It's about 8 inches wide. Draw a circle on it one *foj* in diameter.

A *foj*?? What on Earth is a *foj*?? Well, a *foj* (pronounced 'fudge') is a measurement of length, like the inch or centimetre or smoot. It doesn't matter exactly what size it is – 6" or 150mm is handy in this instance – but the *foj* is a variable unit of measure and could be, say, about the length of a bed if you're trying to sketch a room, or maybe the length of your mains extension lead (although those, like ladders, have a habit of being about 0.9 *foj*).

The point is, here, one *foj* is the *exact* diameter of your circle, and will be used as a scale factor for more circles that will shortly appear. If you have a large piece of paper you could make your *foj* half a metre or more.

Draw a horizontal diameter across the circle. Pencil-in a small numeral 1 just above the line at its left end, inside the circle. It'll look like **Figure 1**.

Draw a smaller circle 1/2 *foj* in diameter, touching the first at the right side of the diameter. Pencil-in a small 2 just outside this circle, above the diameter.

Continue drawing similar smaller circles with diameters 1/3 *foj*, 1/4 *foj*, 1/5 *foj* etc and in the same way label them with numerals equal to the inverse of *foj*: ie, 3, 4, 5 etc.

Draw another such circle 2/3 *foj* in diameter, and label it 3/2 (or 1.5), again touching all the others at the right side, and similarly a circle 5/6 *foj*, labelled 6/5, (or 1.2).

The progression of labels, from left to right, is 1, 1.2, 1.5, 2, 3, 4, etc. Rewrite all labels (in ink this time if you like) by subtracting 1 from each to get the sequence 0, 0.2, 0.5, 1, 2, 3, etc. You now have the resistance circles, r = R/Zo, before you, as shown in **Figure 2**.

Part 2: Reactance circles, x

Next, draw circles, all above the line that touch the diameter at its right side. Make their diameters, measured in *foj*, equal to 2, 1, 2/3, 1/2, 1/3, 1/4, etc. You need not draw the whole circle – just the part inside the largest resistance circle. Label these just to the left of them and inside the large resistance circle. The labels are 1/*foj*, to wit: 0.5, 1, 1.5, 2, 3, 4, etc. These are positive (inductive) reactance circles, x = X/Zo.

Draw another set of these, all below the line, again all touching the diameter at the right side. These are *capacitive reactance* circles. Place a minus sign in front of each of their labels. You have before you a rudimentary Smith Chart – yes, really! And that horizontal line, the line where there is no reactance, has a name – it's called the *real axis*. The chart, to this point, appears in **Figure 3**.

Part 3: An angle scale

Finally, add an angle scale around the edge of the chart, starting with 0° at the left side, 45° at the top, 90° at the right side, and 135° at the bottom. This completes a workable, functioning Smith Chart, and by adding angle tick marks every fifteen degrees, it becomes **Figure 4**. A full clockwise, 360° rotation about the chart corresponds to a

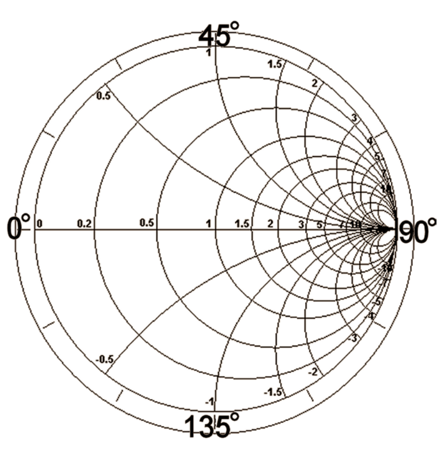

FIGURE 4: Angle scale added.

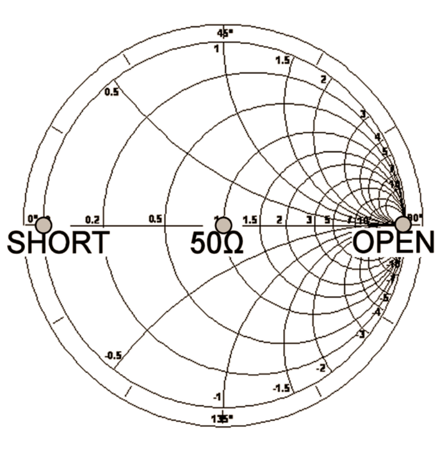

FIGURE 5: Open, short and 50 ohms.

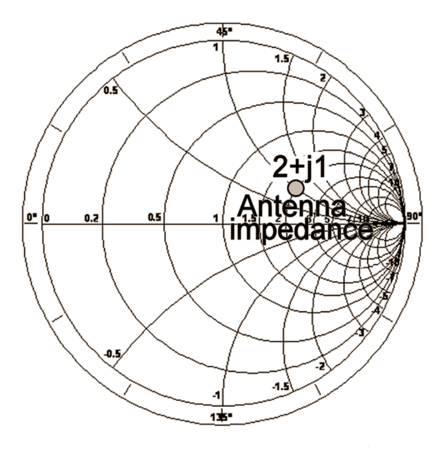

FIGURE 6: Antenna impedance.

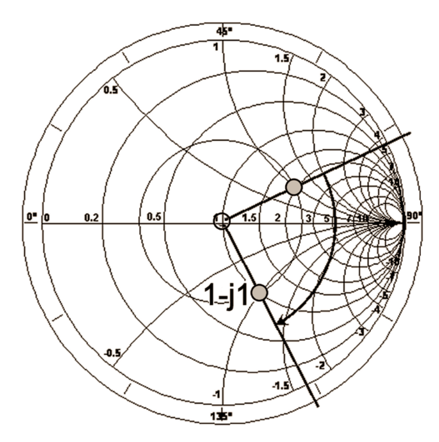

FIGURE 7: 45° move along the coax.

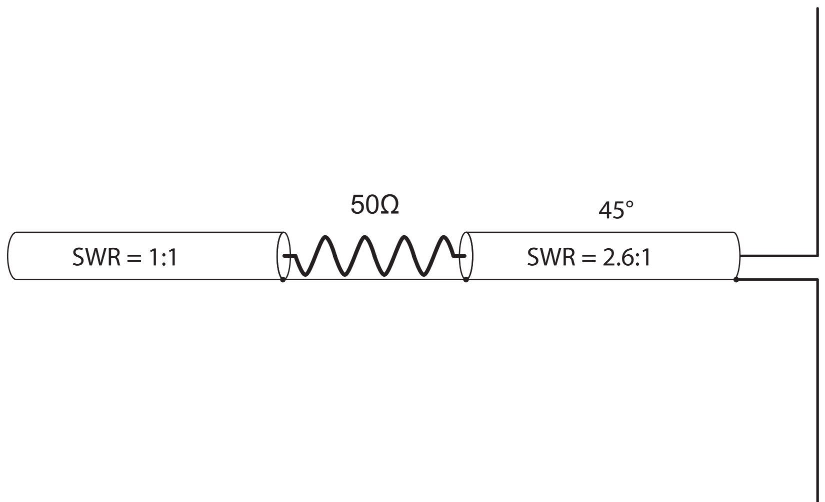

FIGURE 8: Tuned antenna.

half-wave, or 180°, move along the coax toward the transmitter.

What?

This is "de-mystified?" So far all I've done is drawn the chart. Of what use is it? Trust me a bit more when I tell you it helps tune the antenna. To see how, let's borrow a special antenna analyser, a *vector network analyser*, or *VNA* **[2]**. This measures resistance (R) and reactance (X) of a load, and displays the results on a computer-like screen as a Smith Chart. My VNA assumes coax impedance Zo to be 50 ohms.

When connected to nothing, a dot appears at the right side of the real axis. This is on the largest r circle at x = 0 – an open circuit. When the connector is shorted, the dot appears at the left side, at the r = 0, x = 0 point, a short circuit.

When a 50 ohm load is connected, the dot appears in the middle, at r = 1, x = 0 point. This is the point where the impedance is exactly 50 ohms resistance, with no inductive or capacitive reactance: perfect. These points are plotted on **Figure 5**.

Antenna tuning

I'll assume your antenna is a slightly too-long, half wave dipole that, when connected to the VNA, produces a dot on the r = 2 resistance circle and the x = +1 inductive reactance circle, as on **Figure 6**. This tells us the antenna impedance is a resistor of 2x50 ohms, in series with a coil with reactance of 1x50 ohms. Let's tune this antenna.

Draw a circle centred at the chart's centre that passes through the antenna impedance. It crosses the real axis at 2.6, which tells us the SWR on the coax is 2.6:1. Circles about the chart's centre are circles of constant SWR, whose value is the value of r = R/Zo where the circle crosses the real axis at the right side. We can lower this SWR a bit.

Let's move an eighth wavelength along the coax and cut it there. Using the angle scale, we find this to be a 45° clockwise move along the coax toward the transmitter. The SWR does not change. See **Figure 7**.

Connecting the end of this short coax stub to the VNA will show a normalised impedance of z = 1-j1: it's become capacitive! But the impedance now is 50 ohms resistance in series with 50 ohms of capacitive reactance: Z = 50-j50 ohms, as in Figure 7.

To cancel this capacitance, put a 50 ohm (pure) inductance in series with the coax. The SWR from this point back to the transmitter will be 1:1 – ideal! This simple antenna 'tuner' appears in **Figure 8**. Since there is always a point along the coax where z = 1+jx, *this technique can tune any antenna impedance*! All that is needed is a series coil or capacitor of the proper value after a series coax stub of the right length, and the Smith Chart tells us both of these values.

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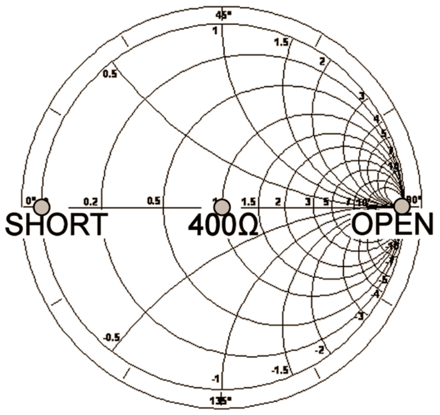

FIGURE 9: Quarter wave 400Ω shorted line.

Another application: a cable balun

A dipole fed with coax should have a balun to keep the RF 'inside' the coax, not 'outside'. *[See also this month's Antennas – Ed].* Let's make a simple example. From the chart, notice that a quarter-wave transmission line, shorted at one end, has a high impedance at the other end.

So – take the coax from the antenna and bend it into a "U" shape, a quarter of a wavelength deep. Space it about five diameters across, thus forming a shorted, parallel-wire transmission line 'Q section' of about 400 ohm line. It will then produce a very high impedance at the antenna as in **Figure 9**, and keep current 'off the outside' of the coax.

You may think this 'balun' has been in the handbooks and other writings since, well, Marconi. But look more closely – many of the others are *4:1 impedance shifting*, balanced-to-unbalanced transformers. *This one is not*! It does a 1:1 balanced-to-unbalanced shift. So don't get confused about how to connect it – most diagrams in the handbooks do something different. **Figure 10** shows this arrangement.

Adding more circles to the chart

To add resistance circles for any r, calculate their diameters: dia = 1/(r+1). For example, if r = 0.4 (R = 20 ohms when Zo **=** 50 ohms), dia = 1/(1.4) (or 0.71 *foj*).

To add other reactance circles x, calculate their diameter from dia. = 1/x. Thus, if x = 0.2 (X = +10 ohms when Zo = 50 ohms), dia = 1/0.2 (or 5 *foj*). Using this simple arithmetic, you can fill in as many circles as you wish. **Figure 11** shows a typical 'professional-grade' Smith Chart of the sort beloved for decades by engineers the world over. With luck you can now see that it's just a version of the one we've drawn here, just with a few more circles and other details added.

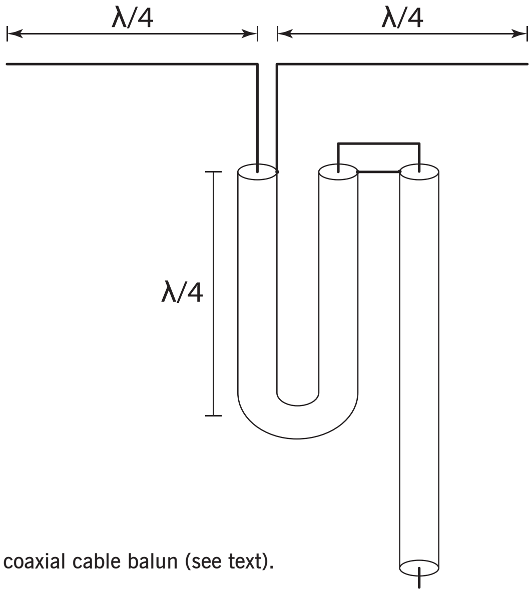

FIGURE 10: 1:1 coaxial cable balun (see text).

Wrapup

Now you know how to draw a Smith Chart, have a fair idea of what it is and how to use it. There's *much* more information on the matter in print and on the internet, a tad more complex than what we've seen here, and there are many more ways to design antenna tuners, all explained and assisted with a Smith Chart. The Smith Chart also has many other uses besides the two simple examples given here. This article is but a brief – but hopefully accessible – introduction to the subject. Enjoy your new knowledge!

References

[1] Philip H, Smith, *Electronics Magazine*, Jan 1939
[2] If you can't borrow one, don't worry. You can use an antenna analyser and work things backward to plot the point on a paper chart.

FIGURE 11: A full-featured professional Smith Chart.