Bootstrap coax traps for antennas

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Abstract

The article is an analysis of an antenna trap where a coil is formed of a length of coax cable, the outer conductor of one coax end is tied to the inner conductor of the other coax end, and the remaining connections (outer at one end and inner at the other) form the terminals for the trap.

1. Bootstrap configuration

There are other configurations using coax cable for antenna traps, so I will call this one a bootstrap configuration to differentiate it from other configurations.

(O'Neil 1981) (N3GO) states that he developed the trap as described, which would appear to mean that he claims to have invented the configuration. (Straw 1997 7.9) refers to the traps as N3GO traps.

(Straw 2003) refers to these traps as W8NX coax traps, which hints a different originator, but it seems W8NX might have written on the subject a decade later (Buxton 1992) than O'Neil (O'Neil 1981), and (Straw 1997) acknowledged them as N3GO traps six years earlier.

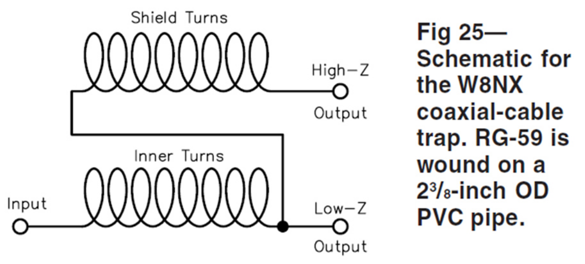


Figure 1:ARRL's explanation

Figure 1 shows the schematic from the ARRL Antenna Handbook (Straw 2003) which represents the inner conductor as simply an inductor, and hints that it might be flux coupled to the inductor formed by the outer surface of the outer conductor. The same approach is peddled in (Straw 2007) and (Silver 2011).

2. Yet another look!

O'Neil's article, and a stream of other articles have attempted to describe how the trap works, and attempt to provide a quantitative analysis of its operation.

None of the articles that I have seen at the time of writing this article (March 2007) consider the coax cable to be a transmission line, and without a convincing argument for why it is not a transmission line, they are suspect.

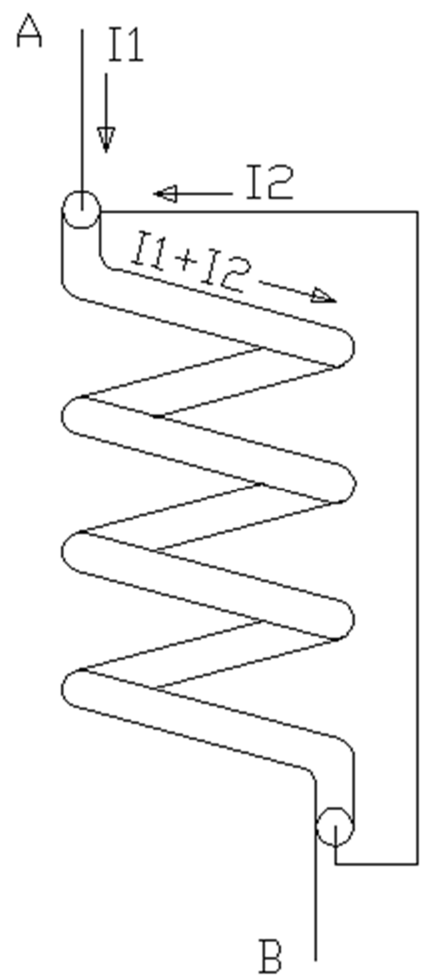


Figure 2: RF circuit of bootstrap coax trap

3. Coax transmission line properties

Before examining the circuit of the trap, lets us refresh the properties of coax transmission lines.

Practical transmission lines at radio frequencies have an outer conductor that is much thicker than the skin depth. For that reason, the current that flows on the outside of the outer conductor can be quite different to the current that flows on the inside of the outer conductor.

In the normal mode of operation of a coax cable (TEM), there are three currents to consider:

- the current flowing on the outside of the inner conductor;
- the current flowing on the inside of the outer conductor, and which is equal in magnitude to the current flowing on the outside of the inner conductor, but opposite in direction; and
- the current flowing on the outside of the outer conductor.

4. Bootstrap trap circuit

Figure 2 shows the trap circuit at radio frequencies (ie where skin effect isolates the inner and outer surfaces of the outer conductor).

5. Coil

The outer of the outer conductor of the coax forms an inductor, albeit an imperfect inductor, so it can be represented as an inductive reactance in series with a resistance. Practical coils have some equivalent self capacitance which would usually be insignificant around the frequency of first trap impedance maximum (resonance), but may become significant at much higher frequencies where a trap is used in a wide range multi-band antenna. A more complete representation is a series inductance and resistance with a small shunt capacitance. The effective coil resistance will usually vary with frequency (a consequence of skin effect). At frequencies well below the coil's self resonance, the inductor can be considered as a simple series equivalent inductive reactance and resistance. The ratio of the inductive reactance (Xl) to the equivalent series resistance (Rl) is known as the Q of the coil (Ql).

6. Current loops

Let's designate the current flowing into trap terminal A as I1, and the current flowing out of the inner conductor at the B end of the coil as I2.

The current flowing out of trap terminal B must equal the current flowing into trap terminal A, so it is also I1.

At the A end of the coax outer, a node if formed by the junction of the inner of the coax outer (current=I1), the outer of the coax outer (current=-(I1+I2)), and the inner of end B of the coax (current=I2), the net current being I1-(I1+I2)+I2 which is 0, so Kirchoff's current law is satisfied.

At the B end of the coax outer, a node if formed by the junction of the inner of the coax outer (current=-I2), the outer of the coax outer (current=I1+I2), and the terminal B lead (current=-I1), the net current being -I2+(I1+I2)-I1 which is 0, so Kirchoff's current law is satisfied.

7. Coax transmission line

Let's designate the voltage between the inner of the coax and the outer of the coax at end A as V1, and the ratio V1/I1 as Z1.

Let's designate the voltage between the inner of the coax and the outer of the coax at end B as V2, and the ratio V2/I2 as Z2.

The transmission line has a complex propagation constant (γ) which (along with the transmission line equations) describes how a traveling wave propagates inside the coax, and a characteristic impedance (Zo) that describes the ratio of V/I in the traveling wave.

It is important to note that V1 may be very different to V2, I1 may be very different to I2, and Z1 may be very different to Z2. Solving the transmission line equations for the specific conditions reveals the relationship.

8. Trap impedance

Estimating the inductor impedance and solving the transmission line equations gives the estimated trap impedance.

The impedance of the trap is given by the expression

$$Z = \frac{Z_0(\cosh(\theta)+1)\left(2Z_l+Z_0.tanh\left(\frac{\theta}{2}\right)\right)}{\cosh(\theta)\left(Z_0+Z_l.tanh(\theta)\right)} \quad ...(1)$$

where:

- Z0 is the characteristic impedance of the coax;
- Zl is the impedance of the inductor formed by the outer conductor of the coax (frequency dependent);
- θ is γ*CoaxLength;
- γ is the complex propagation coefficient for the coax (frequency dependent).

(This expression might look a bit unwieldy, but it calculates in about 1s on a HP50g (from a stored program), and can be calculated in Excel, though you will need to enter the hyperbolic functions expanded as exponentials.)

For a derivation of (1) see (Duffy 2007a).

9. Approximation of trap impedance

When the length of coax is very short wrt wavelength, cosh(θ) approaches 1 and tanh(θ/2) approaches 0, so the above expression can be simplified to Z=4Zl. This approximation will not predict resonance as the proper effect of the inner of the coax has been eliminated, and so is not valid near or above resonance. A fudge to this approximation is to shunt the 4Zl with a value of C that does cause observed resonance. The fudged model gives a reasonable prediction of the X component of Z within an octave of resonance, but the R component is quite different. Since |Z| is dominated by X except very very close to resonance, it will appear that this model also gives a good estimation of measured |Z|.

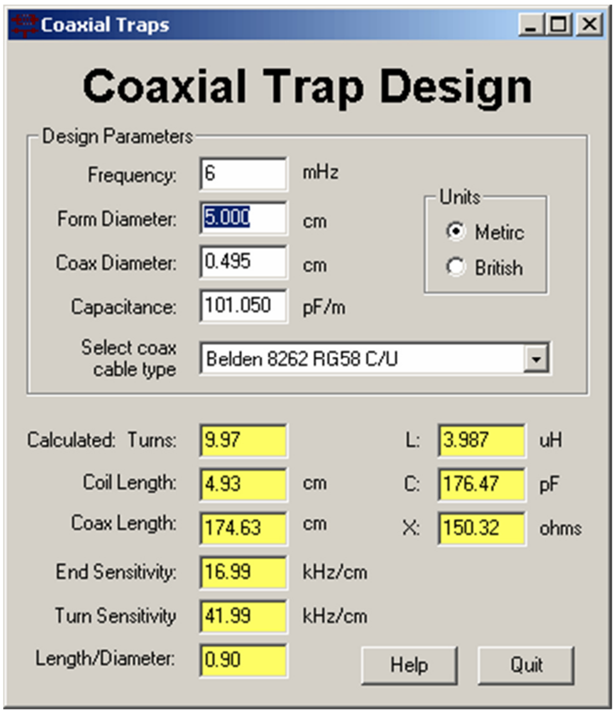


Figure 3: VE6YP design tool

(Muller 2004) takes the coincidence that this fudged model predicts similar X (and therefore |Z|) to assert that the inductor really has twice the number of turns: "As shown in Fig 2, the inner conductor of the coil end is connected to the outer conductor at the beginning. Therefore the current is going around the core two times the number of turns." This plainly ignores skin effect which confines the flux due to current on the inner conductor to the space inside the inner surface of the outer conductor. Having misunderstood the physical inductor, he goes on to develop a flawed rationale to explain the value of C to calibrate resonance to observation.

The trap terminal V/I might suggest there is a Thevenin equivalent circuit (valid over a limited range) for the trap, but that does not explain the implementation. This is a basic premise of Thevenin's theorem, an equivalent circuit describes how the black box terminal V/I behaves but reveals nothing of the internal implementation.

10. A worked example of different configurations

A trap was designed using VE6YP's design tool which appears to embody the formulas that are commonly expressed as describing the resonance of the trap. The design tool gives construction details and calculates the inductance and capacitance of the elements and their reactance at resonance, but does not estimate resistance, or impedance at any frequency.

Figure 3 is the example design from the VE6VP tool. The design was entered into the ON4AA Inductor Calculator to get an estimate of the Q, and a better estimate of the inductance, though there is scope for error as the coil of coax is not a solenoid of round copper wire as assumed by the calculator.

Table 1: Assumptions from ON4AA Inductor Calculator

Item	Value
Inductance	3.71µH
Coil Q	(2*π*f*L)/(270*f^0.5)
Coil equivalent shunt self capacitance	1.3pF

Table 1 shows the assumptions made for a more complete model. The assumptions in Table 1 are not based on measurement, they are based on the inductor calculator and suitable for demonstrating the analysis. The characteristics of the cable, Belden 8262 (RG58C/U) are as derived from Belden's published specifications, and as used and described in the RF Transmission Line Loss Calculator.

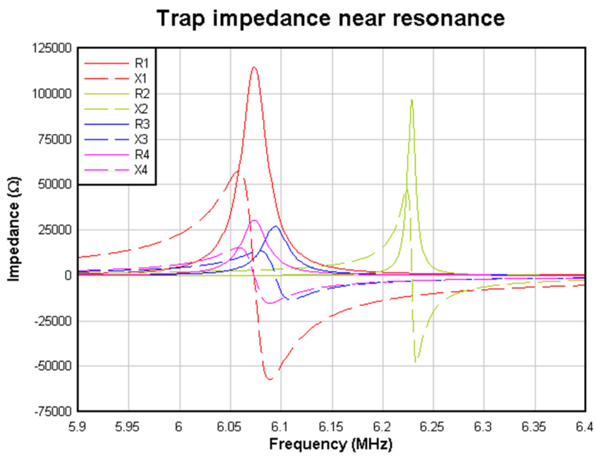


Figure 4: Impedance of trap near resonance

Figure 4 is a plot of R and X of a trap for four different configurations:

- R1, X1 using the bootstrap configuration described in this article;
- R2, X2 using the same inductor and a shunt ideal fixed capacitor of 176pF to form the trap;
- R3, X3 using the same inductor and the o/c coax stub in shunt with the coil to form the trap; and

- R4, X4 using the same inductor connected to one end of the length of coax, and the trap terminals being the other end of the coax.

Configuration 1 is synonymous with ARRL Antenna Handbook 19th edition (Straw 2000), Chapter 7, Fig 20 'High-Z connection'.

Configuration 2 seems consistent with the apparent VE6VP design tool's treatment of the coax (an ideal capacitance proportional to length of the coax). The resonance is displaced due to the different estimate of inductance of the coil.

Configuration 3 treats the coax as a real (ie lossy) o/c stub in shunt with the coil as seems to be done by some analysts.

Configuration 4 is synonymous with ARRL Antenna Handbook 19th edition (Straw 2000), Chapter 7, Fig 20 'Low-Z connection'. It is unclear what purpose the ARRL Antenna Handbook author sees for configuration 4, his 'Low-Z connection'.

The above is not to imply endorsement of the content of the referenced ARRL article.

Clearly, they are all different configurations, with quite different characteristics.

The results for configurations 2 and 3 demonstrate that the bootstrap type coax trap is not well approximated by a conventional tank with a fixed ideal capacitor, nor is is well approximated by merely shunting the inductor by a lossy o/c stub. That suggests that all explanations, tools, and models that ignore the fact the coax behaves as a transmission line are flawed.

11. Prototype trap

Figure 5: Prototype coax trap

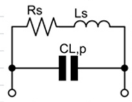
Figure 5 shows the prototype coax trap before cross connection of the ends. It is 10 turns of medium grade RG58C/U type cable close wound on a 50mm PVC pipe, and served with a layer of PVC electrical tape to hold the winding stable during measurements. I would advise against the serving for a real antenna trap, it will retain water which will degrade trap performance.

Ross Beaumont (VK2KRB) made a series of measurements of the trap in different configurations and reported them (Beaumont 2011).

12. Braid inductor

A series of measurements were made of the inductor formed by the outer surface of the outer conductor, using a Q meter.

Braid inductor



CLp (pF)	6.286		
Ls (µH)	3.425	2piLs	21.517

Q meter measurements					Calculation of eqt cct		
f (MHz)	Q	Cdial	Ru	Xu	Rs	XLs	QLsRs
5.000	135	290	0.81	109.8	0.78	107.4	137.9
6.000	147	199	0.91	133.3	0.85	129.2	151.6
7.000	150	144	1.05	157.9	0.97	151.3	156.5
10.000	160	68	1.46	234.1	1.23	214.2	174.8
12.000	160	45	1.84	294.7	1.42	258.6	182.4

Model error	
XLsErr^2	RsErr^2
0.02	0.00017
0.01	0.00028
0.44	0.00000
0.86	0.00012
0.16	0.00023
RMS Error	
0.55	0.01267

Figure 6

Figure 6 is from a spreadsheet calculating a three component equivalent circuit based on the measured data (yellow background). The values of CLp and Ls were found by using the Excel solver to minimise the RMS error between the model and measurements reactance values.

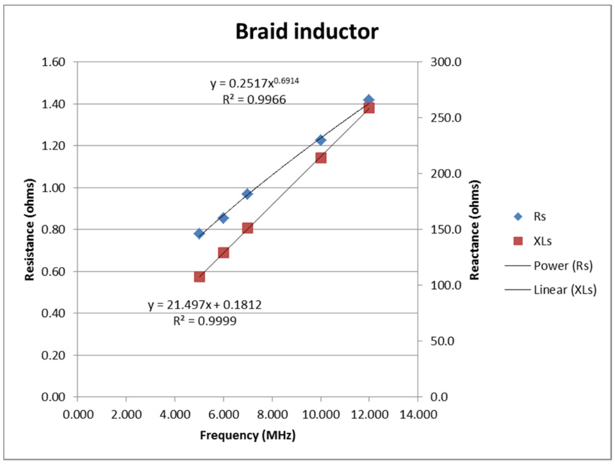


Figure 7

Figure 7 is a plot of Ls and Rs derived from the measured values using the calculated CLp, and curve fits:

- the X points are a very good fit to a straight line X=0.1812+21.497*f; and
- the R points are a quite good fit to R=0.2517*f^0.6914.

The R curve is somewhat surprising. If the inductor was formed of a round copper conductor, and the turns were not too close together, one might expect:

- lower resistance, perhaps one fifth;
- and R∝f^0.5 (Medhurst 1947).

Apparently the effect of the braided conductor and other aspects of the physical coil have not only resulted in significantly higher R, but R∝f^0.7.

The model was then calculated using Ls=3.425µH, CLp=6pF, and R=0.2517*f^0.6914, notwithstanding that rewiring of the device to the bootstrap trap configuration may change CLp slightly.

13. Bootstrap trap

Measurements were also made at a number of frequencies away from resonance.

The braid inductor parameters and coax parameters were used to calculate the bootstrap trap impedance using the expression given earlier in this article.

	Measured		Modelled		Error	
Freq	R	X	R	X	R	X
2.5	3.3	270.0	3.3	262.0	0%	-3%
3.0	4.5	350.0	4.5	341.6	-1%	-2%
3.5	6.3	460.0	6.3	444.1	0%	-3%
4.0	9.1	580.0	9.3	584.7	2%	1%
5.0	27.0	1100.0	28.7	1153.1	6%	5%
7.5	38.0	-1500.0	45.4	-1685.0	19%	12%
8.0	23.0	-1200.0	22.5	-1203.4	-2%	0%

Figure 8

Figure 8 is a tabulation of the measured R and X of the prototype, model for R and X, and a calculation of error.

	Bootrap Coax		LC	
Freq	R	X	R	X
2.5	3.3	262.0	0.5	232.1
3.0	4.5	341.6	0.6	302.9
3.5	6.3	444.1	0.9	394.0
4.0	9.3	584.7	1.2	519.1
5.0	28.7	1153.1	3.4	1024.9
7.5	45.4	-1685.0	4.1	-1518.5
8.0	22.5	-1203.4	1.9	-1084.9

Figure 9

Figure 9 is a comparison of the modelled impedance of the prototype bootstrap coaxtrap with a similar good conventional LC trap. It can be seen that R is larger in the coax trap, about six times at 2.5MHz rising to about 12 times at 8MHz.

14. Comments on some references

(Sommer 1984) treats the interior of the coax as a capacitor calculated from capacitance per unit length, ignoring the distributed inductance... ie denying it is a transmission line, and ignoring its transformation properties in the bootstrap connection.

(Rauch nd) discusses a coax trap, but the trap is of the so-called Lo-Z connection (see Fig 1), not the bootstrap (or Hi-Z connection) discussed in this article.

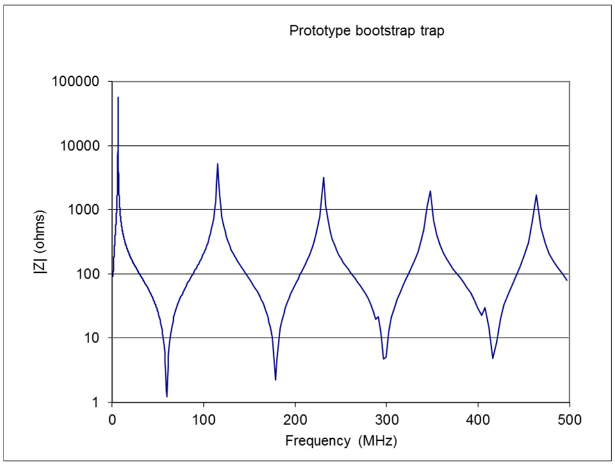


Figure 10: Magnitude of impedance of the prototype trap

Figure 10 is a plot of modelled |Z| of the prototype trap, which reconciles well with measurement.

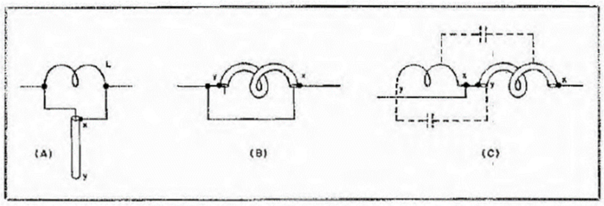


Figure 11

Figure 11 is Fig 1 from (Johns 1981) who explains his equivalent circuit at " ... C as the inner conductor and outer braid coils are separated as shown in Fig 1C and placed end to end. The cross connection is joining the two in series, X to Y. in the middle. The capacitors represented by the dashed lines are representative of the distributed capacitance between the corresponding points of the two coils and the capacitance between inner and outer conductors of the cable. ...". This explanation is the forerunner of several that deny the transmission line effects and pretend the inner and outer conductors are coupled coils, in this case by capacitance. This explanation does not explain higher mode resonances that are evident in Figure 10.

(Shetgen 1984) contains an explanation of the trap that denies that the coil of coax is a transmission line, and pretends that it is simply a pair of coupled coils. This explanation does not explain higher mode resonances that are evident in Figure 10.

(Hall 1985) argues that the bootstrap trap has an equivalent circuit of 4L || C/4. That model will not give higher mode resonances that are evident in Figure 10.

(Muller 2004) argues that the bootstrap trap has an equivalent circuit of 4L || C/4. That model will not give higher mode resonances that are evident in Figure 10.

(Steyer 2010) is another semi traditional explanation of the coax trap as it treats the coax as a capacitor and ignores the impedance transformation due to bootstrapping.

(Silver 2011 21.22) (the latest ARRL handbook) carries the same misinformation, an equivalent circuit for the Hi-Z trap at Fig 21.41 which shows the trap as 4L || C/4. That model will not give higher mode resonances that are evident in Figure 10.

(Portune 2011) is mostly a rehash of early articles, and offers little more than a novel construction technique.

At (Andrea 2012), Bergstrom explains how to determine L and C for a coax trap for "the truth about those mystery traps", as if the coax trap was a simple LC circuit, which it is not.

Google searches suggest there are other relevant documents locked away in the 'members only' archives of QST and not shared with the wider ham community. ARRL has a huge investment in handbooks, journal articles, and discussions that pretend that coax traps are simply LC circuits, in denial of the fact that there is a transmission line component and that it is significant, and they sustain that thinking with new articles from time to time.

15. References

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16. Changes

Version	Date	Description
1.01	14/03/2007	Initial
1.02	14/08/2007	Worked example revised to include configurations 2 to 4
1.03	09/09/2008	Added formula for trap impedance
1.04	23/10/2011	Added prototype trap analysis
1.05	01/01/2016	Conversion to Word 2016