A New Choke Cookbook for the 160–10M Bands
Using Fair-Rite #31 2.4-in o.d. (2631803802) and 4-in o.d. (2631814002) Toroids

Introduction: Common mode chokes are added as series elements to a transmission line to kill common mode current. The line may be a short one carrying audio or control signals between a computer and a radio, video between a computer and a monitor, noisy power wiring, or feedlines for antennas. ***This application note focuses on the use of chokes on the feedlines of high power transmitting antennas to suppress received noise, to minimize RF in the shack (and a neighbor's living room) and to minimize crosstalk between stations in multi-transmitter environments.***

Fundamentals

Differential mode current is the normal transmission of power or other signals inside coax, or between paired conductors. The currents in the two conductors are precisely equal and are out of polarity (that is, flowing in opposite directions at each point along the line). Because the current in the two conductors are equal and out of polarity, they do not radiate, nor do they receive.

Common mode current is carried on the outside of the coax shield, or as the ***difference*** of unequal currents on the two conductors of 2-wire line. A line carrying common mode current acts as antenna for both transmit and receive. Common mode current that couples to the antenna changes the directional pattern of an antenna by filling in the nulls of it's directional pattern. In simple terms, the common mode circuit becomes part of the antenna – the part of it that is close to noise sources picks up that noise; and when transmitting, radiates RF that poorly designed equipment will hear as RF interference.

Series and Parallel Equivalent Circuits: The fundamental equivalent circuit of a ferrite choke at radio frequencies simplifies to two parallel resonant circuits, wired in series, as shown in Fig 1. All ferrite chokes have a ***circuit resonance*** formed by inductance and resistance coupled from the core and parasitic (stray) capacitance between the two ends of the choke. L_C, R_C and C_C describe this ***circuit*** resonance. For a single turn (a wire goes through the core once), the core itself is the dielectric, and the resonance is typically in the range of 150 MHz. We form a choke that is useful at HF by winding multiple turns through the ferrite core. Like all inductors, the inductance (L_C) is multiplied by the square of the number of turns (N^2), and because the resistance is coupled from the core, R_C is also multiplied by N^2. Parasitic capacitance is both through the core and also between turns, and increases approximately linearly with N. The result is that the resonance moves down in frequency and the resistance at resonance gets much larger.

Some ferrite materials also have a property called ***dimensional*** resonance, which is the result of standing waves within the cross section of the ferrite material. Fair-Rite #43 and #61 are NiZn ferrite mixes, and do <u>not</u> exhibit dimensional resonance. Fair-Rite #31, #73, #75, #77, and #78 are MnZn ferrite mixes, and MnZn ferrites <u>do</u> have dimensional resonance. L_D, R_D, and C_D describe the ***dimensional*** resonance (if present). This equivalent circuit describes the impedance of the choke over a broad frequency range – ***once the values of L_D, R_D, C_D, L_C, R_C and C_C; have been found, they are very approximately constant (the same) for a broad range of frequencies.***

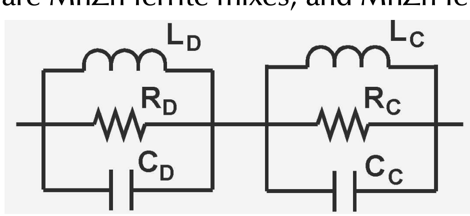


Fig 1

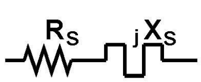


Fig 2

Our measurements of choke impedance provide values of Z_{MAG}, R_S and X_S, as shown in Fig 2, where X_S is positive when the impedance is inductive (below resonance), and negative when it is capacitive (above resonance). Z_{MAG} is the magnitude of the impedance, equal to the square root of $(R_S^2 + X_S^2)$. ***These values are different for every frequency***, but the plotted (or tabulated) data can be used to find L_D, R_D, C_D, L_C, R_C and C_C. When dimensional resonance is not present, these values can be computed by working backwards from the impedance curves. To a first approximation, R_C is simply the value of Z at resonance, L_C is the inductance that yields X_C well below resonance, and C_C is the capacitance that resonates with L_C at the measured resonant frequency. At resonance, of course, R_C and R_S are equal, X_S is zero, and the combined reactances of L_C and C_C is infinitely large. When both resonances are present, the process is significantly more complex.

Understanding the Common Mode Circuit: Consider a simple dipole fed with coax. In the common mode circuit, the coax shield becomes part of the antenna, acting as a single wire connected between one side of the center of the antenna and ground. As a common mode circuit element, its VF is near 0.98 (depending on the diameter of the shield and the dielectric property of the outer jacket). In the common mode circuit, this wire (the coax) has some impedance, (R_S + jX_S), by virtue of its electrical length, which is different at every frequency. At some frequencies, X_S will be positive (inductive), at others it will be negative (capacitive).

Why the Emphasis on R_S? Because X_S of the choke can be inductive or capacitive, and because the common mode circuit will be inductive at some frequencies and capacitive at others, X_S of the choke can cancel part or all of the Xs of the common mode circuit. This cancellation causes common mode current to increase, which is the opposite of the desired result. But R_S of the choke always adds to the common mode impedance, so a high value of R_S always reduces common mode current. Fig 3 shows a choke added to a feedline that looks capacitive at some frequency of interest. In this example, the capacitive and inductive reactances partially cancel, adding to 4,040Ω +j 100Ω. R_S and X_S values for both choke and feedline will be different at every frequency, with X_S values sometimes adding and sometimes cancelling, but R_S values always adding. In effect, a large Value of R_S makes the choke far less sensitive to line length. ***[In the common mode circuit, VF is that of the coax shield with its outer jacket, typically on the order of 0.98, <u>not</u> the VF of the coax as a transmission line. This VF is also typical of 2-wire line in the common mode circuit.]***

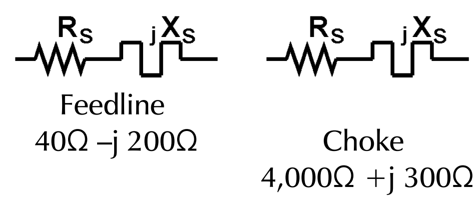


Fig 3

How Much R_S is Needed? From the perspective of both noise suppression and power handling, it has been shown that an R_S value of 5,000 Ω is a good starting point for most applications, such as at the feedpoint of a reasonably well-balanced and well matched antenna at power levels below about 600W. More demanding applications (higher power, a badly unbalanced antenna) may require higher choking impedance, and, in general, more is better. Rewinding a choke to double R_S divides the current by 2, which divides the dissipated power by 2 (because power is I^2R). Using two identical chokes in series divides the total power by 2 and divides the power dissipated in each choke by 4.

Why Chokes Are Needed Without a choke at the feedpoint, the feedline becomes part of the antenna; if the antenna system, including the feedline, is unbalanced, this causes the feedline to radiate part of transmitted power; when receiving, signal and noise picked up by the feedline is coupled to the antenna. This is most easily understood with coax, where skin effect and proximity effect combine to cause common mode current to flow on the outside of the shield and differential mode current to flow on the outside of the center conductor and return on the inside of the shield. Common mode current also flows on parallel 2-wire feedline (where it shows up as the ***difference*** between unequal currents in the two conductors) if any part of the antenna ***system*** is poorly balanced. An antenna system, can be unbalanced (that is, not symmetrical) by its surroundings – unequal heights, ground slope, trees, sloping of the antenna itself, conductive elements of a building or tower very close to it.

Chokes can be used in series to increase their effectiveness on a single band, or to increase their effective bandwidth, or both. Their combined choking impedance is simply the algebraic sum of their R_S and X_S values.

Baluns and Chokes A ***balun*** is used to make a transition between balanced and unbalanced circuitry, and can take many forms. Many are not designed to kill common mode current.

Chokes and Manufactured Antennas My advice is to always use the balun or other matching elements provided with a manufactured antenna (unless you know it to be defective), and to add a common mode choke between that matching element and the feedline to block common mode current.

Rigging Chokes To Beam Antennas A choke is a parallel tuned circuit, and the winding data places the resonance where it is desired for any given antenna. The parallel capacitance is small, typically 4-12 pF; if, for example, we lash coax on either or both sides of the choke so that it runs tight along the boom, capacitance between the coax and the boom appears in parallel with the choke, moving its effective range down in frequency, effectively defeating it. Better to ***rig the choke by suspending it from the boom, lashing coax to the boom at a single point on each side of the choke, and minimizing the length of coax that is in contact.***

Antenna Arrays Chokes are most effective when placed at the feedpoint of each element of an array, but care must be taken to make sure that adding the choke does not change the phasing. A choke is simply a coiled up length of transmission line, and the electrical length of the feedline to that antenna is increased by the electrical length of the feedline used to wind the choke. If the feedline and the choke have the same Z_O, shortening the coax by that electrical length is all that is required. But if Z_O of the choke and feedline are different, the chokes must be added to a model of the array to study their effect and to determine the degree of shortening required.

75 Ω Chokes For 4-Square Transmit Antennas Two possible options are RG302 (0.203 in o.d., solid steel silver coated copper center) and RG179 (0.1-in. o.d., stranded silver coated copper center). RG302 is close enough in size to RG400 that recommendations for RG400 can be used. Grant, KZ1W, sent me some RG179, and I wound chokes on the same test 2.4-in o.d. toroids. (Fig 4) Recommendations are summarized in k9yc.com/ChokesRG179.png and apply to any 0.1-in o.d. coax with FEP or PTFE outer jacket. Loss and dissipation calculations include two 4 in leads. This miniature coax is pretty lossy, so it can't handle a lot of power, but it probably can handle US legal limit power equally divided to each of the verticals ***provided that the chokes are exposed to free air***. Cookbook guidelines are for closely spaced turns (touching on the inner diameter), and are summarized in Table 4.

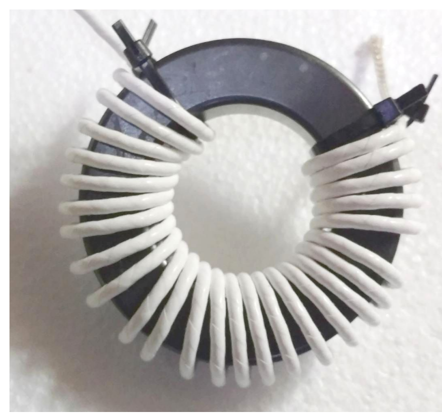


Fig 4 – RG179 Choke

Noise Coupling and Transfer Impedance: Shielded cables have a property often quantified as their ***transfer impedance***, which is the ratio of the differential voltage induced inside the coax to the common mode current on outside of the shield. Its units are Ohms, a low value is better, and the lower limit is the resistance of the shield at the frequency of interest. The overall quality, percent coverage, and uniformity of the shield also contribute to the transfer impedance – a less dense braid or a shield with poor uniformity raise the transfer impedance, causing more noise to couple by this method.

Even with a choke at the feedpoint, most feedlines are ground-referenced at the transmitter end, so any RF will induce current on the shield, which the transfer impedance converts to a differential signal inside the coax. This makes it a receiving antenna for noise. The feedline can also function as a passive element of another antenna nearby, especially vertical antennas. One or more chokes added along the feedline breaks up the common mode circuit, just as egg insulators break up guy wires into non-resonant lengths. I break up the coax feedlines to high dipoles so that they do not act as parasitic elements to my 160M vertical, and the feedlines to my receive antennas to prevent noise coupling via the transfer impedance.

Which Wire/Coax to Use? Over a period of about three months, Glen, W6GJB, and I built, and I measured, hundreds of chokes, wound with RG8-size coax, RG400 (Teflon jacket, stranded silver-coated copper center, two silver-coated copper shields), #12 and #10 enameled copper pairs, THHN #12 and #10 pairs, a #12 teflon pair, and a pair formed by the black and white conductors removed from #10 and #12 Romex (NM).

As part of the project, I built 30-50 ft lengths of each of the paired lines and carefully measured their transmission line characteristics at MF and HF. That measured data, along with details of the measurement system, is in an Appendix. Thanks to their construction and materials, each of these transmission lines has different capacitance between turns and interacts differently with the ferrite core. Z_O depends primarily on dimensions, but dielectric materials affect capacitance between conductors, between turns, and to the core. Z_O is in the range of 45 Ω for enameled pairs (a bit lower for #10), but closer to 96 Ω for the #12 Teflon pair, 90 Ω for THHN and 86 Ω for the NM pair. One should not obsess about adding a 95-100 Ω choke to a 50 Ω feedline – the longest length of line in a THHN choke recommended for 160M is 8 ft long, less than λ/50; the longest in Teflon #12 chokes is 8 ft; the longest in chokes recommended for 80M are proportionally shorter, so still less than λ/50.

Coax types have a minimum bend radius that depends on their construction, and resonance curves are affected by turn spacing and diameter, especially the RG8. We built and measured chokes with 4-in, 6-in, and 8-in diameter turns. Glen provided invaluable assistance by designing (and fabricating in his shop) some very innovative winding forms for the coax chokes, providing the consistency that allowed meaningful measurements to be made, and by winding the larger RG8-size chokes. Glen also built an excellent test fixture that made the measurements possible! Details are in an Appendix.

Which line to use? Chokes wound with higher Z_O line (pairs of #12 THHN, NM, Teflon) work quite well at the feedpoint of a high dipole (or a not very high dipole over poor ground), but may not at the feedpoint of a complex array. The #12 Teflon I found is silver-coated stranded copper, o.d. is 0.109". It's very nice to work with, and chokes wound with it have the lowest loss and the least dissipation for each band. It's expensive, so is best bought from surplus vendors. I paid almost $1/ft, but I've seen long lengths for a bit less. When paired, Z_O will vary with insulation thickness and the dielectric properties of the insulation. The other "best" choice, especially for antennas with feedpoint Z_O near 50 Ω, is RG400. Harbor Industries RG400 is highly regarded, $230 for 100 ft on EBay. If these cables are too rich for your blood, the next best choice is white and black conductors which are easily removed from NM cable (Romex) by stripping the outer jacket. It has been observed that the jacket of THHN deteriorates with exposure to UV, which may change transmission line properties of paired THHN.

Enameled copper pairs have much greater loss than other paired lines. This is because the magnetic fields produced by currents in very closely spaced pairs used as transmission line cause the current to be concentrated in the side of the conductors closest to each other. This mechanism, which is strongly related to skin effect, is called ***proximity effect***, and is what causes differential current to flow on the inside of the coax shield. Just as skin effect forces current to the skin of the conductor, proximity effect forces it to only one half of the skin! Proximity effect rises rapidly as the center-to-center spacing approaches the conductor diameter, which is the case with enameled wire. As can be seen from the table of measured transmission line data, the enameled pairs have significantly higher loss (and greater dissipation) than other paired cables. It's also possible for the enamel to be scraped by the ferrite core during winding, shorting to the core at multiple points and significantly degrading choke performance. For both reasons, ***I no longer recommend chokes with enameled wire.***

How the Cookbooks are Organized: For each band and cable type, designs are listed in order of highest to lowest value of R_S. For chokes covering multiple bands, that ranking is determined by the band having the lowest R_S value.

Table 1 – Choke Cookbook For Chokes Wound on a Single #31 4-in o.d. Toroid

RG400	Teflon #12	NM/THHN #12
160M:		
23 turns (17KΩ)	22-23 turns (15KΩ)	21-23 turns (12.5KΩ)
22 turns (15KΩ)	21 turns (13.5KΩ)	20 turns (12KΩ)
21 turns (13KΩ)	20 turns (12.5KΩ)	19 turns (11KΩ)
20 turns (11KΩ)	19 turns (11KΩ)	18 turns (10KΩ)
19 turns (10KΩ)	18 turns (10KΩ)	17 turns (8.5KΩ)
18 turns (8KΩ)	17 turns (8KΩ)	16 turns (7KΩ)
17 turns (7KΩ)	16 turns (6.5KΩ)	15 turns (6KΩ)
16 turns (5.5KΩ)	15 turns (5.5KΩ)	
80M:		
18-20 turns (11KΩ)	16-18 turns (7.5KΩ)	15-16 turns (6.7KΩ)
21 turns (10KΩ)	15 turns (7.2KΩ)	17 turns (6.5KΩ)
17 turns (9.5KΩ))	19 turns (7KΩ)	14 turns (6.4KΩ)
22 turns (9KΩ)	14 turns (6.5KΩ)	18 turns (6.2KΩ)
16 turns (8.5KΩ)	20-21 turns (6KΩ)	19 turns (5.5KΩ)
23 turns (7.5KΩ)	17 turns (5.5KΩ)	13 turns (5.5KΩ)
15 turns (7.5KΩ)	13 turns (5.5KΩ)	20 turns (5KΩ)
14 turns (6.5KΩ)		
13 turns (5.5KΩ)		
40M:		
14 turns (7.5KΩ)	13-14 turns (5.7KΩ)	12-14 turns (5KΩ)
16 turns (7.5KΩ)	19 turns (5KΩ)	
15 turns (7KΩ)	12 turns (5.2KΩ)	
13 turns (6.5KΩ)	15 turns (5KΩ)	
17 turns (6KΩ)		
18 turns (5.5KΩ)		
12 turns (5KΩ)		
30M:		
13-14 turns (6.5KΩ)	13-14 turns (5KΩ)	
12 turns (6KΩ)		
20M:		
12 turns (6KΩ)		
160-80M:		
21 turns (13KΩ 160M, 10KΩ 80M)	18 turns (9.5KΩ160M, 8KΩ 80M)	17 turns (8.5KΩ160M, 6.5KΩ 80M)
20 turns (11KΩ 160M, 11KΩ 80M)	17 turns (8KΩ both bands)	16 turns (7KΩ160M, 6.5KΩ 80M)
19 turns (10KΩ 160M, 11KΩ 80M)	20 turns (12.5KΩ160M, 6KΩ 80M)	18 turns (10KΩ160M, 6KΩ 80M)
22 turns (15KΩ 160M, 9KΩ 80M)	19 turns (11KΩ160M, 7KΩ 80M)	15 turns (6KΩ160M, 6.8KΩ 80M)
18 turns (8KΩ 160M,10KΩ 80M)	16 turns (6.5KΩ160M, 8KΩ 80M)	19 turns (11KΩ160M, 5.5KΩ 80M)
23 turns (17KΩ 160M, 7.5KΩ 80M)	15 turns (5.5KΩ160M, 7.2KΩ 80M)	20 turns (12KΩ160M, 5KΩ 80M)
17 turns (7KΩ 160M, 9.5KΩ 80M)	21 turns (13.5KΩ160M, 5.5KΩ 80M)	
16 turns (5.5KΩ 160M, 8.5KΩ 80M)		
160-40M:		
17 turns (7KΩ 160M, 9.5KΩ 80M, 6KΩ 40M)	15 turns (5.5K 160M, 72K 80M, 5K 40M)	
18 turns (8KΩ 160M,10.5KΩ 80M, 5.5KΩ 40M)		
19 turns (10KΩ 160M, 11KΩ 80M, 5KΩ 40M)		
16 turns (5.5KΩ 160M, 8.5KΩ 80M, 7.5KΩ 40M)		

RG400	Teflon #12	NM/THHN #12
160-30M:		
16 turns (5.5KΩ 160M, 8.5KΩ 80M), 7.5 KΩ 40M, 5 KΩ 40M)		
80-40M:		
16 turns (8.5KΩ 80M), 7.5 KΩ 40M) 15 turns (7.5KΩ 80M, 7KΩ 40M) 14 turns (6.5KΩ 80M, 7.5KΩ 40M) 17 turns (9.5KΩ 80M, 6KΩ 40M) 18 turns (9.5KΩ 80M, 5.5KΩ 40M) 19 turns (11KΩ 80M, 5KΩ 40M)	14 turns (6.5KΩ 80M, 5.8KΩ 40M) 13 turns (5.8K both bands) 15 turns (7.2KΩ 80M, 5.5KΩ 40M)	14 turns (6.5KΩ 80M, 5KΩ 40M) 13 turns (5.5KΩ 80M, 5KΩ 40M)
80-30M:		
16 turns (8.5KΩ 80M), 7.5 KΩ 40M, 5 KΩ 30M) 15 turns (7.5KΩ 80M, 7KΩ 40M, 5 KΩ 30M) 14 turns (6.5KΩ 80M, 7.5KΩ 40M, 6.5KΩ 30M)	13 turns (5.8KΩ 80M-40M, 5KΩ 30M)	

4-inch o.d. Chokes for Multiple Bands: A few designs provide good choking impedance (an R_S value of 5KΩ or more) over three harmonically related bands. 16-19 turns of RG400, and 15 turns of a #12 Teflon pair, all provide 5KΩ from 160M to 40M. Many of the RG400 designs provide very high choking impedance on both 160 and 80M, while a few of the #12 Teflon NM/THHN designs provide at least 10KΩ on 160M and at least 7KΩ on 80M.

Table 2 – Choke Cookbook For Chokes Wound on a Single #31 2.4 in o.d. Toroid

RG400	Teflon #12	NM/THHN #12
160M:		
18 turns (10KΩ)	18 turns (9.5KΩ)	18 turns (9.5KΩ)
17 turns (6KΩ)	17 turns (7KΩ)	17 turns (9KΩ)
		16 turns (6KΩ)
80M:		
16 turns (8KΩ)	15-16 turns (6.5KΩ)	15 turns (7KΩ)
15 turns (7KΩ)	17 turns (5.5KΩ)	14 turns (6KΩ))
14 turns (6KΩ)	14 turns (5.8KΩ)	16 turns (5KΩ))
17 turns (5.5KΩ)		13 turns (5KΩ)
13 turns (5KΩ)		
40M:		
14 turns (6.2KΩ)	15 turns (6.5KΩ)	14 turns (6KΩ)
15 turns (5.4KΩ)	14 turns (5.8KΩ)	13 turns (5KΩ)
13 turns (5KΩ)	13 turns (5KΩ)	
30M:		
14 turns (6.5KΩ)	14 turns (6KΩ)	13-14 turns (5.5KΩ)
13 turns (5.5KΩ)	15 turns (5.5KΩ)	
12 turns (5KΩ)	13 turns (5KΩ)	
20M:		
13 turns (5.4KΩ)	13 turns (5.5KΩ)	12-13 turns (5KΩ)
14 turns (5KΩ)	14 turns (5KΩ)	11 turns (4.2KΩ)
12 turns (5KΩ)	12 turns (5KΩ)	
15M:		
11-12 turns (4.8KΩ)	11-12 turns (4.7KΩ)	11 turns (5KΩ)
10 turns (4.2KΩ)	10 turns (4KΩ)	12 turns (4KΩ)
	13 turns (3.8KΩ)	10turns (4KΩ)
10M:		
10 turns (4.4KΩ)	10 turns (4.3KΩ)	10-11 turns (4.2KΩ)
9 turns (3.8KΩ)	11 turns (4KΩ)	
11 turns (3.5KΩ)		
160-80M:		
17 turns (6KΩ 160M, 6K 80M)	17 turns (7.5KΩ 160M, 5.5K 80M)	16 turns (6KΩ 160M, 5K 80M)
80-30M:		
	15 turns (6.5KΩ 80-40, 5.5K 30M)	14 turns (6KΩ 80-40, 5.5 KΩ 30M)
80-20M:		
14 turns (6KΩ 80-30M, 5K 20M)	14 turns (5.8KΩ 80-40M, 6KΩ 30M, 5K 20M)	13 turns (5KΩ all bands)
13 turns (5KΩ all four bands)	13 turns (5KΩ all four bands)	
40-15M:		
13 turns (4.8KΩ 40-30M, 5KΩ 20M, 4.8KΩ 15M)	12 turns (4.6KΩ 40-30M, 5KΩ 20M, 4.8KΩ 15M)	

Chokes in Series: In general, any combination of chokes can be used in series to provide the desired choking impedance over the desired bandwidth. Their combined choking impedance, R_S, will be the sum of their R_S values on each band. For example, two 12-turn RG400 or Teflon chokes provide at least 8KΩ from 80 to 15M and 6KΩ on 10M. Combining 14 and 17 turn RG400 chokes provides more than 8KΩ on 160M, about 12KΩ on 80M, 8KΩ on 40M, 7KΩ on 30M, and 5KΩ on 20M. Table 3 lists combinations I found.

The spreadsheets at the links in Table 5 show R_S values, attenuation, dissipation, and approximate cost and weight for all chokes measured for each band. Use these spreadsheets to find other combinations useful for your station.

Table 3 – 2.4-in o.d. #31 Single Toroid Chokes in Series to Cover Multiple Bands

RG400	Teflon #12	NM/THHN #12
160-80M:		
Two 17 turn chokes (12KΩ)	Two 17 turn chokes (14KΩ 160M, 12KΩ 160M) Two 16 turn chokes (8KΩ 160M, 13KΩ 80M, 7K 40M)	Two 16 turn chokes (11-12KΩ)
160-40M:		
Two 15 turn chokes (6KΩ 160M, 14KΩ 80M, 11K 40M)	Two 15 turn chokes (6.5KΩ 160M, 14KΩ 80M, 7K 40M)	Two 15 turn chokes (6.5KΩ 160M, 14KΩ 80M, 7K 40M)
160-30M:		
Two 15 turn chokes (6KΩ 160M, 14KΩ 80M, 11K 40M, 6.5KΩ 30M)	Two 14 turn chokes (6KΩ 160M, 14KΩ 80M, 11K 40M, 6.5KΩ 30M)	Two 14 turn chokes (5KΩ 160M, 12KΩ 80M-40M)
160-20M:		
One 14 turn choke and one 17 turn choke (8KΩ 160M, 12KΩ 80M, 8K 40M, 7KΩ 30M, 5KΩ 20M)		
80-30M:		
Two 14 turn chokes (12KΩ)	Two 13 turn chokes (10KΩ)	Two 14 turn chokes (12KΩ 80M-40M, 11KΩ 30M)
40-15M:		
Two 12 turn chokes (9.5KΩ), 6KΩ on 10M	Two 11 turn chokes (8KΩ 40-20M, 9KΩ on 15M)	Two 12 turn chokes (9KΩ 40-20M, 8KΩ on 15M)
40-10M:		
Two 11 turn chokes (8KΩ), 7KΩ on 10M	Two 10 turn chokes (6.5K 40M, 7KΩ 30-20M, 8KΩ 15-10M)	Two 11 turn chokes (8KΩ 40-20M, 9KΩ 15M, 8K 10M)
30-10M:		
Two 10 turn chokes (7KΩ 30-20M, 8.5KΩ 15-10M)	Two 10-11 turn chokes	Two 10-11 turn chokes

Table 4 – RG179 Chokes for Transmitting 4-Square Arrays on 2.4-in o.d. #31 Toroids

Band	Winding
160M	27 turns
80M	24 turns
40M	22 turns
30M	21 turns

	2.4-in o.d. Toroid	4-in .d. Toroid
RG400	http://k9yc.com/Chokes-2r4inRG400.png	http://k9yc.com/Chokes-4inRG400.png
Teflon	http://k9yc.com/Chokes-2r4inTeflon.png	http://k9yc.com/Chokes-4inTeflon.png
NM/THHN	http://k9yc.com/Chokes-2r4inNM.png	http://k9yc.com/Chokes-4inNM.png

Table 5 – Links to Spreadsheets

The Spreadsheets

The R_S Data: Values are coded with colors and bold type to indicate their relative values. Black indicates R_S of 5K or more; Black Bold is a step up, red (not bold) is the next step up, and Bold Red is very high R_S. Grey indicates bands where the choke may be useful in series with another choke to provide the desired R_S.

Attenuation is computed for the length of wire needed to wind the choke with some additional length for leads, and is based on my measurements of each wire type for each band. The greatest attenuation for a recommended choke on a recommended band is 0.06 dB for Teflon, 0.07 dB for RG400, and 0.1 dB for NM. ***(Exception: RG179 has approximately twice the loss of RG400.)***

Dissipation and Power Handling

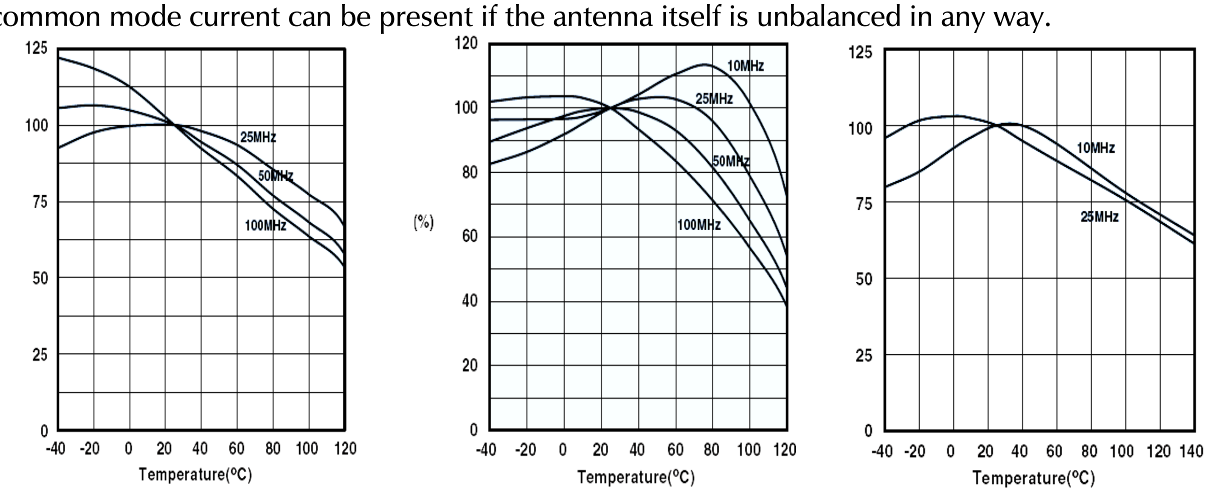
Dissipation in a choke is the sum of two components.

Differential Mode Dissipation: This is the dissipation inside the winding due to normal power flow through the resistance of its conductors at the operating frequency for 1,500W key down. The spreadsheet computes this from the attenuation. (Below UHF, virtually all dissipation is due to conductor resistance for practical line types in good condition). Worst case differential mode dissipation in the portion of the feedline that forms the choke (that is, transmission line loss) for a recommended choke is 20W, and for most recommended chokes is 15W or less.

Common Mode Dissipation: A high value of R_S increases the ability of the choke to handle higher transmit power. Dissipation due to common mode current is I^2R_S, where R_S is the series equivalent resistance of the choke and I is the common mode current. Because power is current squared, it falls twice as fast as R is increased, so power approaches zero with very high R_S.

Common mode dissipation can be estimated in an NEC model by adding the feedline as a single wire in the model (approximating as closely as possible it's actual path from antenna to shack) and adding a Load equal to $R_S + jX_S$ at the point(s) where the choke(s) is (are) to be inserted. The added wire should be connected to one side of the antenna, to ground at the other end, should be the diameter of the coax shield or twice the diameter of the paired conductors, and insulation corresponding to the outer jacket of the coax.

A two-wire feedline terminated in the shack to an inductively coupled input may not be ground referenced. The tuner schematic should be studied to determine whether this is true (if there's a ground on the antenna side of the transformer, it's ground referenced). Such a system does not eliminate the need for a choke – without one, the feedline is still connected to the antenna, and common mode current can be present if the antenna itself is unbalanced in any way.



#43 Material #31 Material #73 Material

Fig 5 – Impedance vs. Frequency and Temperature as a percentage of impedance at 25°C

Temperature The permeability of ferrite materials varies as a function of both frequency and temperature, and different mixes behave very differently (Fig 5). Any RF current that produces a field in the ferrite will cause heating in the ferrite (and IR losses in the wire). If the current is small enough, and if the choke is exposed to free air, the heat will be radiated and/or conducted as fast as it is produced. Larger currents, however, can cause temperature to increase. In the #43 and #73 materials, this will in turn cause permeability to fall, which in turn allows more current, which produces more heating. In other words, thermal runaway can occur if the current is large enough and the core is small enough.

At some high temperature (the Curie temperature), the ferrite will temporarily lose its magnetic properties (until it cools). The Curie temperature is different for each mix. The #31 material has somewhat better temperature characteristics, especially on the lower HF bands, where impedance actually increases with temperature up to about 100°C, but a rather low Curie temperature. Thermal runaway can still occur, but is a bit less likely. ***In general, it is important to use ferrites in a manner that 1) saturation is avoided***, and ***2) permeability does not significantly drop with temperature.***

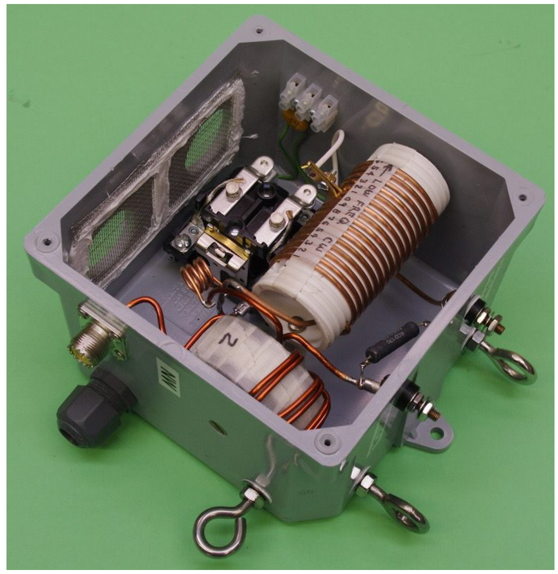


Fig 6 – Ventilated Enclosure

Avoid Putting Transmitting Chokes In Enclosures – it greatly reduces the transfer of heat to ambient air, and can easily cause destructive overheating. In general, it's best to leave the choke exposed to air, weather-proofing connections as needed.

In the process of upgrading the N6RO super-station, Gary Johnson, NA6O, carefully studied this issue in the lab, and came to the conclusion that any enclosure for a transmitting choke should be ventilated. Fig 6 shows an enclosure Gary made for matching and switching in one of the 4-squares. Ventilation holes, protected by wire mesh, are on the right in the photo, and face downward when the enclosure is installed. In the photo, the choke, wound with enameled wire, is mounted to the lower side of the enclosure

Avoid conductive enclosures – chassis-mounted coax connectors would short out the choke, and even if insulated, stray capacitance between the choke and the enclosure would likely detune it.

Duty cycle: The importance of dissipation is destructive heating of the choke, both of the core and conductors. For contesting and DXing, duty cycles of 20-33% are typical for CW and SSB and in the range of 35-40% with WSJT modes, but can exceed 50% with RTTY. Longer transmissions typical of ragchewing can increase short term heating, damaging the choke. Power handling is maximized when the choke by maximizing is exposed to free air, and by maximizing R_S.

Weight and Cost Estimates: Weight can be important if the choke is at the feedpoint of a wire antenna. The spreadsheet includes estimates of both weight and cost. They include the core(s), the coax or paired wires, connectors, and a simple frame or structure needed to build the choke. Estimates are conservative (high) – they assume, for example, two Amphenol silver plated, Teflon dielectric connectors, with silver reducers when needed for RG400. While Teflon insulated wire and coax is expensive, relatively short lengths are required.

An Important Note About Measured R_S Values

While these values are tabulated to four digits from cursor readouts on my measured data, they should be viewed has being no closer than +/-10% to chokes that we wind. That's because ferrite cores are a rather wide tolerance part! Fair-Rite's specifications for their suppression products are for minimum values of impedance at several spot frequencies for a single turn through a core. Quoting the data sheet for a 2.4-in #31 core:

> ***"Suppression cable cores are controlled for impedances only. Minimum impedance values are specified for the + marked frequencies. The minimum impedance is typically the listed impedance less 20%."***

Attempting to account for this wide tolerance, before developing the new Cookbooks, I characterized more than 250 toroids – 200 2.4-in o.d. toroids and 75 4-in o.d. toroids. 90 of the 2.4-in cores were from my "stash" or loaned by NCCC members N3ZZ, K6GT, and W6GJB, all accumulated over a span of 12 years. The remainder were purchased as a lot of 10 in May 2018 and a lot of 100 in June from well known industrial vendors. I labeled each toroid with an identifier, wound ten turns of a very flexible RG58 patch cable around it, made a log frequency sweep of its impedance from 1-30 MHz, and saved the data as a screen plot of Z_{MAG}, R_S, and X_S, with cursor readouts for principal ham bands. Z_{MAG}, R_S, and X_S values were transferred to a spreadsheet, and four samples were selected at the high and low limits of R_S and X_S at 1.8 MHz for the both sizes of the recently purchased cores.

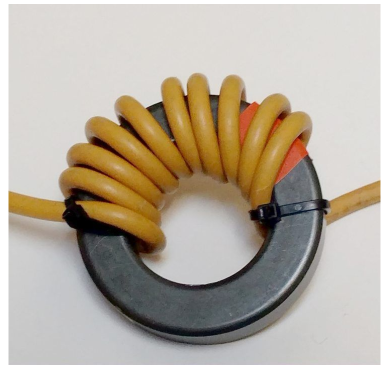


Fig 7 – The Test Winding

This study revealed extremely wide variations in the fundamental properties of the 2.4-in cores purchased over a period of 12 years, and variations of +/-10% for the newly purchased cores. These variations have profound effects on the characteristics of chokes wound on these cores. A choke wound on a lower µ' core can have much lower choking impedance on the lower bands than on an "average" µ' core for the same number of turns and winding style! But that lower µ' core will yield much greater choking impedance on the higher HF bands because resonance occurs at a higher frequency. Compare, for example, the impedance below about 5 MHz for these 10 turn chokes wound with RG58 on three different #31 2.4-in o.d. toroid cores.
http://k9yc.com/TestL109-31.png http://k9yc.com/TestL3B31.png http://k9yc.com/TestL3A31.png
The differences are entirely due to their inductance, which in turn is the result of the cores having different µ' values.

For the Cookbook, chokes using the three cable types were wound and measured on each of these cores, and cursor readouts for the ham bands transferred to a spreadsheet. R_S values for each choke are the lowest at each frequency for the four toroids on which they were measured. Details of my measurement setup are in Appendix Two.

There is no question about the mix of the cores I've measured – Fair-Rite is the manufacturer of virtually all ferrite toroids commonly used by hams, and each of the mixes we use has a distinctly different curve of impedance vs. frequency. See k9yc.com\Fair-Rite.pdf and k9yc.com\2TurnTests.pdf

Your Mileage Will Vary, depending on the luck of the draw for any toroid you happen to choose! In general, the widest variations in R_S from one toroid to another are at the upper and lower ends of the useful range of each choke. By measuring so many toroids and chokes, I've tried to increase the likelihood that the chokes we wind will have R_S higher than Cookbook values. And when you see choke data published by others, ask them how many cores they measured!

<u>**Winding Guidelines**</u>

Starting The Winding: Wind a cable tie around the cross section of the toroid where you want to start the winding and pull it not quite tight. Feed the cable through the toroid from below, and use another cable tie to secure it to the first one, leaving enough free cable to connect the choke when it is complete. I like to snip the end cable ties with a half inch or so remaining that I can use needle-nose pliers (or even my teeth) to tighten it, then snip them cleanly when I'm finished winding. The choke in Fig 8 starts at 3 o'clock and is wound counterclockwise around the core.

Fig 8 – An RG400 Choke

Wind In Sequence: Take care that turns are wound in order – out of sequence turns can cancel. Turns can be continued on a second layer when the first layer is filled by overlaying the starting turns of the winding. In Fig 9, the winding starts at the upper left, completely fills the first layer around the core, and continues with five more turns overlaying the start of the winding.

Turn Spacing: Measured data are for windings tight to the core, with adjacent windings touching on the inside of the core.

Paired Lines: Take care that pairs are not twisted as they are wound. Twisting can reduce choking impedance. Using different colors for the two conductors makes it easier to see twisting, and also to count turns. Solid conductors are preferred over stranded because turns tend to stay in place. Stranded wire is much less disciplined, although the #12 Teflon wire I found tends not to have that problem, with turns staying in place pretty well. The pair was shorted for measurement. Leads for both of the chokes shown were purposely cut short for measurement – long leads add measurement error.

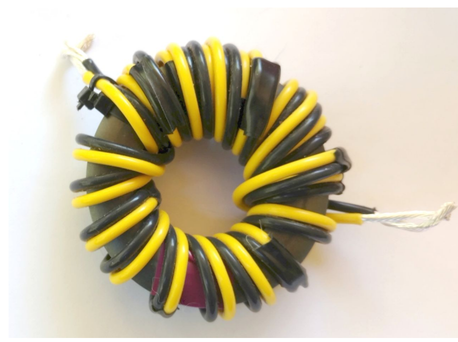


Fig 9 – A Teflon Choke

Maintain polarity between the two ends of the choke – that is, make sure that the same conductor of a parallel pair is connected to the coax shield at both ends of the choke. This is especially important with arrays, and can be an issue with lightning protection for a choke added to the line not at the feedpoint. If the polarity is reversed, the choke will still work but the array won't, and static buildup on a coax shield may not be as well discharged.

Pairing the wire: Loss, VF, and Z_O data are for the paired conductors touching, held in place every 3-6 inches with Scotch 33 or 35 (because they are thinner than 88, it can help squeeze an extra turn on 2.4-in chokes for 160M). Wider spacing will increase Z_O and decrease attenuation, especially with enameled pairs (because proximity effect is reduced).

Enameled wire: Contact with the core while winding and positioning turns tends to scratch the insulation from enameled wire, allowing windings to make random electrical contact with the core, seriously degrading performance. I experienced this with high quality enameled wire. Given this issue and that both loss and differential mode dissipation in enameled pairs due to proximity effect are double that of RG400, winding chokes with enameled wire is not recommended, and no cookbook data has been developed.

RG8, RG213, RG11, RG6: For several reasons, I am no longer including these coax types in the Cookbook. The chokes are heavier, more expensive, and have greater loss (because they use more cores and more coax). Designs are repeatable only if turns pass through the core(s) sequentially, and if they have the same radius and spacing. That's not easy to do with these sizes of coax.

Additional Considerations For Chokes Wound on 2.4-in o.d. Cores:

Two Cores or One? Winding a choke on two cores rather than one doubles the inductance and approximately doubles the value of stray capacitance in parallel with that inductance. This has the effect of dividing the resonant frequency by 2 and doubling the impedance at resonance. Compare, for example, 13 turn chokes wound with NM12 on one core and two cores. http://k9yc.com/240-1-NM12-13T.png and http://k9yc.com/240-2-NM12-13T.png

Transmission Line Data

These data were obtained from S11 for short lengths with the far end open and the far end shorted, post processed using AC6LA's ZPlots Excel spreadsheet. An SDRKits VNWA3e was used for the S11 measurements.

Line Type	Z_O @ 5 MHz	VF @ 5 MHz	10 MHz Loss
#12 THHN Solid	91.2 Ω	.725	1.2 dB/100 ft
#10 THHN Stranded	92.4 Ω	.73	1.5 dB/100 ft
#12 Teflon (Ag/Cu)	96.6 Ω	.833	.76 dB/100 ft
#10 NM	86 Ω	.725	1.5 dB/100 ft
#12 NM	91 Ω	.73	1.2 dB/100 ft
#12 Enameled	43.4 Ω	.77	2.45 dB/100 ft
#10 Enameled	41.3 Ω	.66	2.36 dB/100 ft
RG400	50.8 Ω	.69	1.22 dB/100 ft

Notes On the Data: The significantly greater loss in the enameled pairs as compared to THHN and NM pairs is the result of ***proximity effect***. The higher Z_O of the Teflon wire pairs is the result of it's lower dielectric constant as compared to PVC insulated NM/THHN wire.

Construction Ideas

Here are two of W6GJB's ideas for integrating chokes with the center insulator for a dipole. The rope in Fig 10 is Vectran, a very strong material, but one that has poor UV resistance. Glen has built a dozen or so of these in several variations. All of the penetrations of the tubing are very well sealed. The same tubular construction can be used for "inline" chokes to break up the feedline by mounting SO239 connectors on both end-caps.

Fig 10

Glen's latest concepts is shown in Figs 11 and 12 (next page). At left, before weather-proofing; at right, Glen holds the completed insulator, rigged at the center of his 80M dipole, ready to raise. The wire for the dipole is #9 hard drawn bare copper, the green loops are #12 stranded THHN (so that the connections to the antenna can flex in the wind). Copper split-bolts are used to connect the stranded #12 to the solid #9. Glen built a few like this, using a structure of GPO3 fiberglass, a high voltage electrical material, with high fiber volume fraction and good structural properties. He quickly abandoned that material because of the very unhealthy fiber particles generated as his CNC router cut the parts. A UV resistant Lexan is under consideration. Fig 12 shows two inline chokes for 160M. They are wound for 160M, and used in feedlines for high dipoles to prevent their interaction with my 160M Tee vertical. The black tape on the form of the RG400 choke provides UV protection for some "liquid" electrical tape. No, he doesn't want to build and sell any of these things.

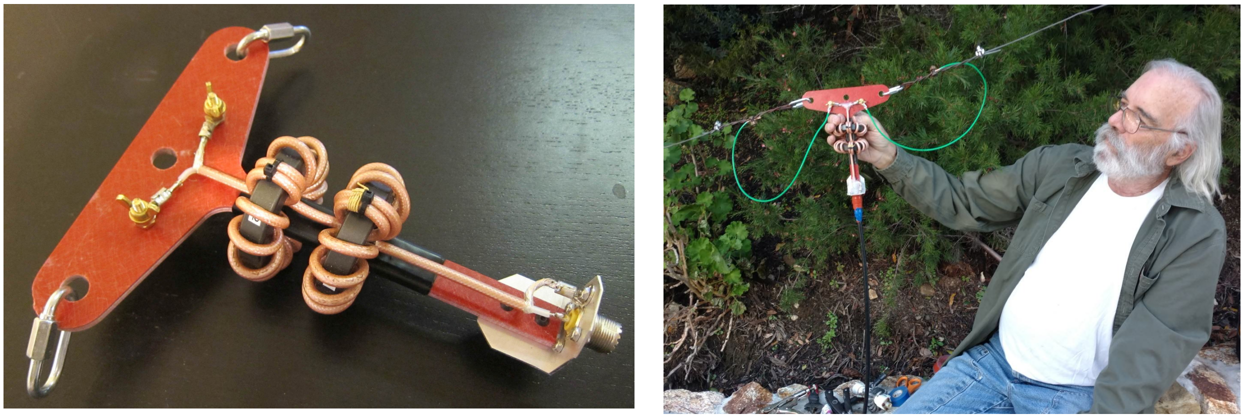


Fig 11 – W6GJB’s Dipole Center Insulator With Two RG400 Chokes

Fig 12 – W6GJB’s Inline Chokes

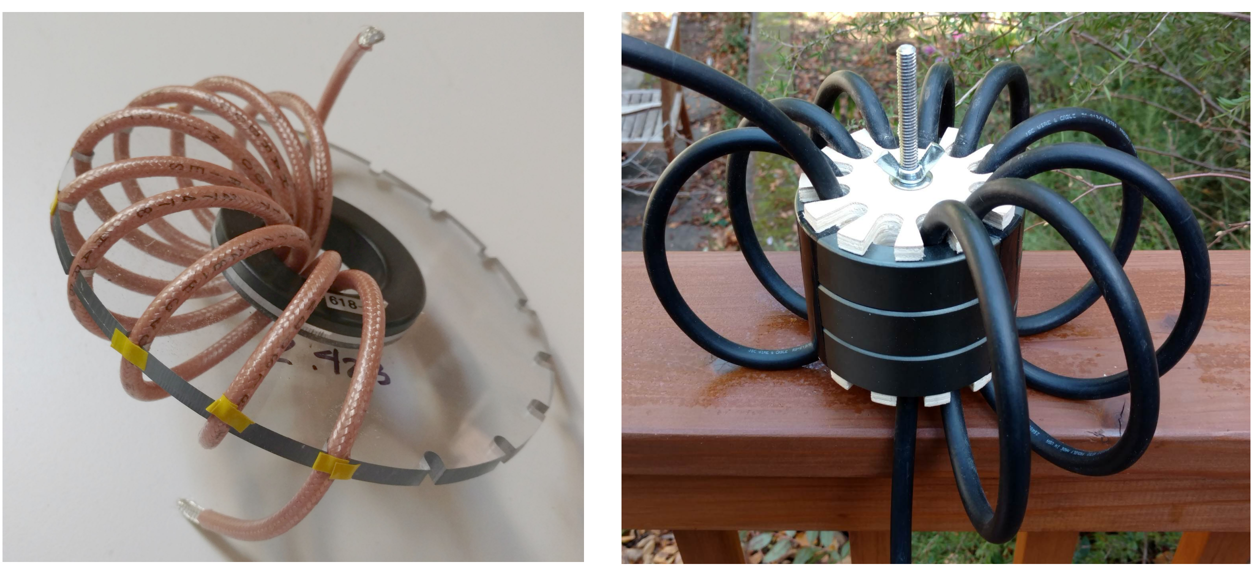


Fig 13 – Two Of the Many Forms W6GJB Built To Measure Coax Chokes

For my research, Glen designed several special forms and built nearly a dozen chokes with specified bend radii of 1, 4, 6, and 8 inches. Not only would the forms be difficult for most hams to build, the resulting chokes would have been expensive and weren't all that useful. Two are shown in Fig 13. It was not possible to get consistent or meaningful measurements without those forms to discipline the windings, and even with the forms, the resulting chokes were never the best for a given application. The Lexan form to fit the 2.4-in o.d. cores presented a surprising challenge – there's enough "slop" in their o.d. that each form had to be custom milled to fit it's assigned core, as indicated by the "magic marker" annotation on the Lexan!

Acknowledgements

Thanks to N3ZZ, K6GT, and W6GJB for loan of cores for this work, and to numerous hams who, by asking questions, have both improved my writing about it and caused me to investigate new avenues. Most notable is GM3SEK, who caused me to investigate bifilar chokes wound on a single core, and subsequently, chokes wound with RG400 coax.

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<u>Appendix</u>

Transmission Line Data

These data were obtained by measuring S11 for 30-50 ft lengths of each cable type with the far end open and with the far end shorted, then post processed using AC6LA's ZPlots Excel spreadsheet. For each dataset, three plots are shown. The last of the three is un-smoothed raw data as input to ZPlots. By curve-fitting, ZPlots computes K0, K1, and K2, which are parameters for a model devised by Johnson and Graham and used by major manufacturers (including Belden and Times Microwave) to plot the data for their cables, and by SimSmith to model cable parameters. The First two plots were computed by ZPlots from K0, K1, and K2.

#12 THHN Pair: Zo (nom) = 90 Ω, VF (nom) = 0.728, 1.2 dB/100 ft @ 10 MHz, K0=0.000012, K1=0.203588, K2=0.055205

#12 Y/BK (Teflon) Pair: Zo (nom) = 96 Ω, VF (nom) = 0.834, 0.76 dB/100 ft @ 10 MHz, K0=0.000013, K1=0.098622, K2=0.044982

#10 THHN Pair: Zo (nom) = 90.95 Ω, VF (nom) = 0.7491, 1.5 dB/100 ft @ 10 MHz, K0=0.000008, K1=0.278518, K2=0.060604

#10 NM Pair (w/o ground): Zo (nom) = 84.44 Ω, VF (nom) = 0.7368, 1.5 dB/100 ft @ 10 MHz, K0=0.000003, K1=0.275865, K2=0.047031

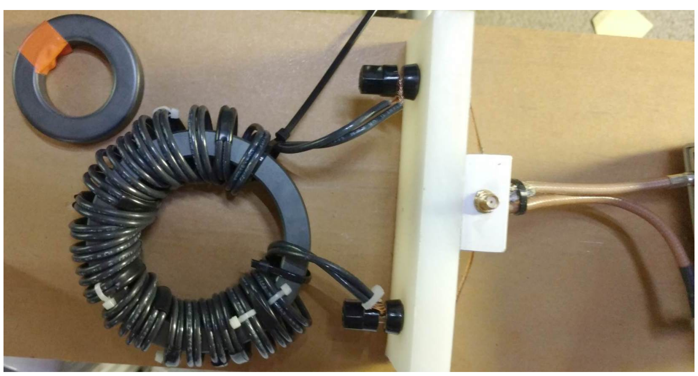
#10 Enameled Pair: Zo (nom) = 40.5 Ω, VF (nom) = 0.7435, 2.36 dB/100 ft @ 10 MHz, K0=0.000014, K1=-.409901, K2=0.106527

RG400: Zo (nom) = 49.76 Ω, VF (nom) = 0.703, 1.225 dB/100 ft @ 10 MHz, K0=0.000014, K1=0.364280, K2=0.0088752

Complete data, including plots vs. frequency of Zo, VF, and Loss is at http://k9yc.com/ChokesTLData.pdf

The Measurement Setup For Chokes

Chokes were measured with an SDR Kits VNWA 3E. For the measurement, W6GJB built a test fixture based on my conceptual design that places the choke in series between the input and output of the VNWA, forming a voltage divider between the choke and the 50Ω input impedance of the VNWA. The VNWA was calibrated to a measurement plane at the point where the choke is inserted, and S21 (the gain from output to input) is measured.



4-in o.d. THHN Choke In Test Fixture

Understanding The Plots

In a vector network analyzer, S21 is complex – that is, the result contains both magnitude and phase data. Math functions built into DG8SAQ's VNWA software solves the voltage divider equation to convert S21 (the voltage divider ratio) to Z_{MAG}, R_S, and X_S. The Blue curve is S21, Orange is Z_{MAG}, Magenta is R_S, Black is X_S. Values for each parameter are displayed by a table of markers placed at the limits of the 160, 80, and 40M bands, and at points near the 30, 20, 15, and

10M bands. Values are in Ohms. The sweeps, approximately 60 seconds long, use 4,192 data points, logarithmically spaced. Data tends to be noisy for high values of Z_{MAG}, so a running average was applied to smooth it. The flat sections of each plot at the left and right of each curve are the result of this smoothing.

When comparing plots, note that the scales are varied from one choke to another for the best view of the data. Vertical units/division are shown along the left axis; a log frequency axis is always used, but its limits vary.