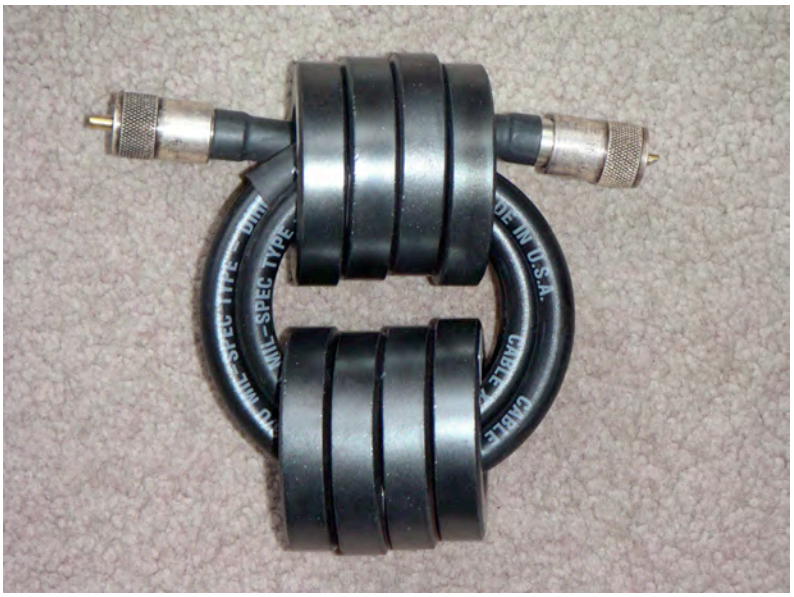
Common-Mode Chokes[1]

by

Chuck Counselman, W1HIS

Summary

Your ability to hear weak MF and HF signals is limited by noise, generated mostly by solid-state electronic switches within your own house, conducted *via* the 60-Hz power line to your shack, and from there to your antenna by common-mode current on the feedline. Putting common-mode chokes on your feedline, power, and other cables will substantially reduce your received noise level. A good choke has >> 1 kΩ impedance for all MF and HF bands and costs $12 (for a small cable) to $120 (for a large, QRO cable).



QRO common-mode choke for RG-213/U, made with eight ferrite toroids costing $5 ea. Its impedance is >1 kΩ from 1.8 to 18 MHz and 550 Ω at 30 MHz. Put one of these at your antenna feedpoint, another at the amp. output, and a third in-between.

"One of life's most economical ways to increase receiving performance."

— K1VR

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[**Why this gobbledegook?!** Only to preserve the option of expanding and/or adapting this article and submitting it for publication to a wider audience, *e.g.*, *via* the ARRL. Many publishers (I don't know about the ARRL yet) will not consider an article that is already in the public domain, that has been published previously, and/or for which the author does not own the copyright. I am **not** trying to make a buck here.]

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1. Introduction

This article tells **what** common-mode chokes are, **why** and **where** to use them, and **how** to make ones that **work well, at minimal cost** both in time and in dollars.

Skip the first part of the next section if you know what a common-mode choke is; but please do look at subsection ***2.1. Ferrite***, where I explain my choice of ferrite "mixes" for common-mode chokes and warn of a ***safety hazard*** relating to this choice.

Even if you know something about why and where to use common-mode chokes, I hope you'll get worthwhile new ideas from the sections on those topics.

The last section of this article tells how I make common-mode chokes for various applications, good enough but as inexpensively as possible for the application.

How good is "good enough"? That's the topic of the next-to last section.

This article is a work in progress. Tell me about errors and omissions you find, and I'll try to fix them, giving due credit to you. Ask questions. I hope to add a FAQ list and/or more Appendices, and to increment it/them over time, to avoid having to edit the main text frequently.

2. What Is a Common-Mode Choke?

First, what is a choke? By a choke I mean a radio frequency (RF) choke — a discrete device that you can insert or connect in series with a wire or a cable to reduce substantially the RF current flowing along the wire or cable at the insertion point. The ideal choke has infinite impedance for RF; inserting it would be equivalent, for RF, to cutting the wire or cable. How much impedance is sufficient in practice, I discuss below.

To define "common mode," I must define "mode." The concept involves nothing beyond electricity and eighth-grade algebra. Consider a cable of two insulated wires, like zip cord. Imagine this cable delivering power to a 12-VDC lamp. The current flowing in one wire of this cable has the same magnitude as the current in the other wire, but the currents flow in opposite directions. For a 24-W lamp the magnitude of the current in either wire would be 2 A. The net current in the cable (*i.e.*, the algebraic sum, considering both the magnitudes and the directions, or signs, of the currents in the individual wires) would be zero.

We have just discussed the two possible modes of current flow in a two-conductor cable. These are the "differential" mode and the "common" mode. The differential mode is also known as the "transmission-line" mode. In the example, 2 A flows in the differential mode, and 0 (zero) A flows in the common mode. The differential or transmission-line

current is equal to the algebraic or "signed" difference between the currents in the two wires, divided by two. The common-mode current is the algebraic sum, or net current in the cable.

In another example, imagine connecting the two wires of a piece of zip cord together at each end, in other words connecting the wires in parallel, to obtain a single conductor able to carry twice as much current as either wire could carry by itself. In this zip cord, zero current will flow in transmission-line mode; whatever current flows (depending on the application) will be common-mode current.

In different situations (which you can imagine), non-zero values of current may flow in both modes: the transmission-line mode and the common mode.

RF currents (unlike DC) vary with position along a cable, and their amplitudes are complex (having magnitudes and angles, or real and imaginary parts); however, the concepts of transmission-line and common-mode apply at any cross-sectional plane; and the complex amplitudes are added and subtracted algebraically.

A cable may have more than two conductors. An N-conductor cable has N independent modes of current flow. Of these modes, the only one that interests us here is the common mode. For any number of conductors in a cable, the common-mode current is the algebraic (signed) sum of the currents in all the conductors.

A common-mode choke for use in an N-conductor cable has N insulated conductors, one for each conductor of the cable. An *ideal* common-mode choke is perfectly transparent in every mode except the common mode. It offers no resistance (or reactance) to any differential or transmission-line current; but, for the common mode, it looks like an open circuit. In other words, the perfect common-mode choke has infinite impedance in the common mode.

To be perfectly transparent in every mode except the common mode, the common-mode choke must be like the cable in such respects as conductor size and current rating, insulation thickness and voltage rating, and — for an RF transmission line — characteristic impedance. The simplest way to make a common-mode choke transparent is to make it from a piece of the same type of cable. Then, to give the choke a high common-mode impedance, you surround this piece of cable with ferrite.

2.1. Ferrite

Ferrite is a ceramic material, made like pottery or bricks, by firing in an oven. Ferrite contains iron and other ferromagnetic elements in oxidation and crystallographic states such that the ferrite has high magnetic permeability (μ) and very low electrical conductivity (σ). If a cable is surrounded by ferrite, then the magnetic field encircling the cable due to common-mode current in the cable magnetizes the ferrite. Because the magnetic permeability of ferrite is very much greater than that of air, the amount of energy stored magnetically in the ferrite is very great. Thus, the inductance per unit length of cable surrounded by ferrite is very high. A common mode choke is an inductor having a high value of inductance. The impedance (Z) of an inductor is proportional to frequency (f) and is given by

$$Z = 2 \pi i f L,$$

in which *i* is the square root of minus one and L is the inductance. I discuss below how high the magnitude of Z must be for the choke to do the job expected of it. In any case, knowing this magnitude and the frequency, you can calculate how much inductance the choke must have. The inductance is proportional to the energy stored magnetically in the choke. This energy, in turn, is proportional to the amount (mass or volume) of ferrite in the choke. The proportionality constant is determined by the geometry of the choke, *i.e.*, by the shape of the ferrite and how it fits around the cable. Some geometries are much more effective than others, in that they store much more magnetic energy and make a much higher-inductance (better) choke per unit mass, or per dollar cost, of ferrite.

Before getting to geometry, I need to say a few words about ferrite materials. There are many kinds of ferrite material, made by mixing different ingredients together and processing (*e.g.*, grinding, cooking, and annealing) the "mix" differently.

Different mixes have different properties. To make a common-mode choke for MF and HF (the 160- through 10-m ham bands), I like to use Fair-Rite Products Corp. <http://www.fair-rite.com/> mix number 31 or 43. Other mixes work better or just as well in particular applications, and I use other mixes. However, these two are all I need. Actually, either one of these two would do, but mix 31 is more cost-effective for smaller chokes, and mix 43 is more cost-effective for larger chokes, *e.g.*, for the larger coaxial cables needed with high-power transmitters. Using two mixes, 31 and 43, is an engineering compromise.

The reason why many different mixes are made is that ferrites are imperfect materials. Some work best at UHF, others at VHF, others at HF, others at MF, and so on down through the spectrum, through audio, to DC. Some are very lossy, which is not entirely bad for RFI suppression; whereas others have low loss, which is obviously better in a transformer core. A crucial compromise, or trade-off, involves loss and magnetic permeability.

In a common-mode choke we want high permeability, for high stored energy, high inductance, and high common-mode choking impedance with low mass / volume / dollar cost of ferrite. Unfortunately, with high permeability comes high loss. High loss means that the choke looks like a low-Q inductor. In other words, it looks like a resistor in series with a perfect inductor. Current flowing through a resistor dissipates power and makes heat. In a common-mode choke in the antenna feedline of a 1500-W ham station, dissipation due to common-mode current through an inadequate choke can easily heat the ferrite enough to crack it and to melt the cable. A thermal-runaway process occurs, because ferrite loses its ferromagnetism above its so-called Curie temperature. The choke's inductive reactance vanishes, so the choke becomes even more inadequate, and the common-mode current increases; but the choke's series resistance does not vanish, so the dissipation and rate of heating increase.

My choices of Fair-Rite Products mixes 31 and 43 are compromises between the conflicting values of low loss, and high permeability. Other mixes have much less loss, and still others have much greater permeability. Mixes 31 and 43 have the highest permeabilities that you can get, with losses still low enough (if your common-mode choke has sufficiently high impedance, as discussed below) that the common-mode current (I) through the choke will be sufficiently small that the power (I^2R) dissipated in

the choke's equivalent series resistance (R) will be sufficiently small and the resulting temperature rise will not be not unsafe, even if you are transmitting 1500 W.

The condition "if your common-mode choke has sufficiently high impedance" here is **crucial**. Compromise on choking impedance and your choke will fail catastrophically, taking your coax with it, possibly setting fire to your house, and — worst of all — terminating the best run you've ever had, in the most important DX contest of your life. Do not tempt Mr. Murphy. You have been warned.

I won't tell you to use a lower-loss, lower-permeability ferrite because I know you wouldn't. With lower permeability, you'd have to use more ferrite, which would cost more. I know you wouldn't spend more money just for safety's sake. Hams are the cheapest people in the world.

I won't tell you to use anything more lossy than mixes 31 and 43 because I use them myself. Incidentally, of these two, mix 43 has less loss and is the one I use for higher-RF-power chokes.

3. Why Use Common-Mode Chokes?

The most common reasons for using common-mode chokes are:

(1) to reduce the fraction of the RF power that is fed to your antenna from your transmitter, but then is conducted back to your shack *via* common-mode current on your feedline, causing RFI trouble in the shack or elsewhere in your house;

(2) to keep the transmitted RF power that 60-Hz power, telephone, TV, and other cables in the field of your antenna pick up, from bothering susceptible devices connected to these cables in your own and neighbors' houses; and

(3**)** to keep the RF noise that all the electronic devices in your house generate, from being conducted *via* 60-Hz power, telephone and other cables to the outer shield of your radio, and from there along your feedline(s) to your antenna(s), in common-mode.

Reasons (1) and (2) are obvious and compelling. When your logging computer crashes or your spouse is screaming, you have to do something. Reason (3) is more subtle and ignorable. Even when QRM and QRN are obliterating half the stations on the band — hell, 90% of the signals — you can continue operating and having fun. There are still plenty of stations strong enough to work. Reason (3) matters only to a serious DXer or contester, but it is one of the most economical of all ways of improving receiving performance.

A significant fraction, typically -15 dB, of the noise power arriving at an antenna feedpoint *via* common-mode current on the feedline is coupled into the antenna's receiving mode, because a typical balun (adequate for transmitting purposes) has this much residual imbalance, and also because a nominally balanced antenna is never perfectly balanced.

A common-mode choke is reciprocal. It reflects and absorbs transmitted power that would otherwise be conducted from your antenna back to your shack and onto your 60-Hz power and other circuits to bother, say, your telephone, by the same factors or numbers of dB as it does for QRN going in the opposite direction.

If your antenna is highly directional, as a Yagi or a Beverage is, then you have another reason to use a common-mode choke: to prevent reception of QRM and QRN by your feedline as opposed to your antenna. Without a good common-mode choke in the feedline at its feedpoint, your potentially excellent antenna's 25- or 30-dB front-to-back or front-to-side ratio could be reduced to 15 or even 10 dB.

In the HF hamshacks that I've visited, the background noise level heard on most HF bands (especially the low bands) could be reduced by more than an S-unit by means of common-mode choking. In some cases (which I could name but won't, to avoid embarrassing my friends) I was able to reduce the received noise level by four or five S-units. I reduced my *own* received noise level on the low bands by even *more*.

For years I've been a regular participant in CW nets on the 80- and 40-m ham bands, and in SSB nets on MARS frequencies near these bands. I hear better than anyone else in these nets. I am often the *only* participant able to copy every one of the dozen or two dozen stations in a net. Why can I hear so exceptionally well? My receiver is nothing special, nor is my antenna; it's a wire just 23 to 40 feet high. Nor is my QTH very quiet. I have a small lot in a dense suburb, just two miles from Cambridge and three miles from Boston**. I hear exceptionally well because I have good common-mode chokes** in my antenna feedline, in the other cables connected to my radio, and also in the cables connected to the worst of the QRN sources in my house.

A typical American household contains more than a hundred significant QRN sources. Some of these sources, *e.g*., incandescent light dimmers, fill the MF and HF spectrum with noise in periodic bursts or impulses at the 60-Hz power-line frequency (or at 120 Hz). In a SSB receiver (even more in an AM receiver) this noise sounds like a steady buzz, and its strength doesn't change if you tune a few tens of kHz.

Switching power supplies, which are in all kinds of electronic appliances, in the battery chargers of portable devices, in the solid-state electronic "ballasts" of fluorescent lamps, and in the "solid-state transformers" of low-voltage incandescent lighting systems, generate relatively narrow-bandwidth, hum-modulated, QRN at harmonics of their switching frequencies, usually in the 15-25 kHz range. These frequencies are not very stable, but drift and fluctuate with temperature, power-line voltage, and load current.

Digital-electronic circuitry is ubiquitous (not just in computers) and usually switches at stable frequencies. Digital electronics generates QRN most often with discrete spectra and quasi-periodic, often complex, but regular temporal structure. However, some digital-electronic sources of QRN have very broad spectra, or spectra with such broad peaks, that the QRN can be mistaken for natural "white" noise in a communications receiver. Also, the typical house contains so many independent sources of QRN that, although their individual spectra may be peaky, the composite spectrum can sound pretty flat.

Many or most of these sources continue to generate QRN even when the appliance or device is switched "off." Many of them, *e.g*., video and audio entertainment devices, computers and related devices, telephones and related devices, clocks and timers in all sorts of devices, and (probably worst of all) alarm systems, contain batteries or supercapacitors and continue to generate QRN even after AC power is disconnected by unplug ging the device/system or flipping a circuit-breaker.

4. Where to Use Common-Mode Chokes

Most hams would benefit from installing common-mode chokes in many places. *I* sure did! I had to install a couple of chokes before I could transmit even low power on 15 meters without triggering a fire alarm. When I got an amp, I could trigger the alarm by transmitting on any of several bands. Installing more chokes, in more places, solved this problem.

When I first moved into my present QTH, even before I began hamming here, I had to install several common-mode chokes to stop hearing loud audio QRM in my telephones, from the amplitude modulation of two nearby broadcast stations. In addition to music and speech, in certain 'phones I also heard a constant hum or buzz, because the broadcast carrier signals were being 60-Hz-AC-modulated by nonlinear conductors within my house. A long story, with a happy ending thanks to more common-mode chokes.

My QRO HF TX got into the telephones and whole-house audio entertainment system of my neighbors across the street. Fortunately for me, their telephones and computer modems were already being clobbered by the local AM broadcast stations. Solving those problems made me a hero. I solved all of my neighbors' RFI problems with common-mode chokes. Along the way, I installed a few more common-mode chokes to eliminate the QRN I'd been hearing from the solid-state transformers in their low-voltage lighting circuits.

In my own house and yard I've installed many, many common-mode chokes to eliminate QRN from many, many, ***many***(!) light-dimmers, compact fluorescent lamps, electric blanket controls, computers, computer peripherals and networking devices, TV sets, VCRs, garage-door openers, etc. One of the worst QRN sources in my house, until I muted it with common-mode chokes, was the intrusion- and fire-alarm system.

An unbelievably large number of small and seemingly innocuous devices, like the battery-recharging base of my cordless electric toothbrush, and a tiny 4-watt night-light (photoelectrically switched), were generating noxious QRN. Our air bed's control system was both a source and a victim of RFI. Its variable-speed pump pulsed in response to the syllables of "Whiskey One Hotel India Sierra" when I worked 3YØX on 20-m SSB. As Don Greenbaum remarked, I was a lucky ham to have an XYL who got pumped up by my DXing.

Your HF noise background is almost certainly being raised, and your ability to hear weak signals is being impaired, by the noise generated by electrical / electronic devices in your house. Unless you've sniffed around with a shielded, B-field-sensing loop and a battery-powered HF receiver as I have,[2] you probably don't know what or where most of these QRN sources are. I was amazed by how many I found in my own house. As soon as I silenced one (with a common-mode choke), I could hear another, which I located and silenced in turn. With each additional common-mode choke (or trashing of the offending device), my received noise level dropped lower.

[2] **Appendix 2**, to be included in a future draft of this article, will address noise-sniffing.

So here's where to put common-mode chokes:

First,

- on a coaxial feedline near the feedpoint of any antenna; or, if you run balanced line from the feedpoint of a balanced antenna to a balanced tuner and balun (or balun and unbalanced tuner) at, say, the point of entry to your house, on the coax at this point;[3]
- on a coaxial feedline on both sides of any point where the coax shield is connected to a rod or pipe driven into the ground, or to a counterpoise;[4]
- on a coaxial feedline in your shack, where the coax first reaches your tuner, amp, or transceiver;
- on a long coaxial feedline, at intervals of one-quarter wavelength;[5]
- on any other cable that goes near your antennas, *e.g.*, to a rotator, to a remote tuner or relay/switchbox, to SteppIR motors, to tower lights or utility outlets, …;
- on the power cable at an outdoor compact fluorescent lamp if this cable runs anywhere near your antennas, and also where this cable enters your house;
- on both the high- and the low-voltage sides of any solid-state transformer that feeds low-voltage lighting near your antennas;
- at the ground-fault circuit interrupter (GFCI) of any AC power circuit that goes near your antenna.[6]

Second,

- on every 60-Hz AC power cable that feeds your shack;[7]
- on every other cable (antenna-rotator, telephone, TV, computer network, etc.) that comes into your shack;
- on every cable of every computer, peripheral, keyer, TNC, switching power supply (including wall warts and battery chargers, especially laptop-computer power adaptors) and other device connected to your radio that oscillates, switches, or digitates;

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[3] An effective common-mode choke can made for a balanced feedline as well as for coax. For example, see the common-mode chokes on the 100-Ω balanced lines in the 4:1 current balun described in **Appendix 4**.

[4] The low-pass T-network formed by two chokes with a "ground" between them is significantly more effective than the same chokes would be without the ground, and much more effective than the ground alone would be.

[5] Two common-mode chokes separated by a quarter-wavelength work better than the same two chokes in series, together in one place, because reflection of the common-mode wave by the high-Z lump posed by one choke causes an impedance minimum to appear one-quarter wavelength away. N (>2) chokes distributed over a quarter wavelength work better than the same N chokes bunched together in one place.

[6] By code, every outdoor circuit must have a GFCI. RF can trip these devices. Worse, some of these devices generate QRN. Some even generate QRM! In my house one was generating strong intermod products, in the 160- and 80-m ham bands, from the signals of local AM broadcast stations. (Replacing this GFCI with a new one eliminated the problem.)

[7] You may have more than one 120-V branch circuit, plus a 240-V circuit for your amp. Each of these circuits should also have an L-C, difference-mode, EMI filter. **See Appendix 5**.

- on the AC line cable/cord of any compact fluorescent lamp or any incandescent lamp with a dimmer and/or solid-state transformer that is plugged into your shack circuits.[8]

Third,

- at any identified QRN source in or around your house;[9]
- on the cables of an intrusion/fire/other alarm system, at panels, multiplexers, telephone-line interfaces, radio-telemetry interfaces, 60-Hz power supplies, standby battery charger/supplies, etc.;
- on TV cables, both where they enter your house and where they reach TV sets, converters, VCRs, DVRs, cable modems, etc.;
- on 60-Hz AC power cables and any audio and video cables connected to TV sets, music and "home theater" systems, etc.;[10]
- on telephone cables, both where they enter your house and where they reach telephone sets, answering machines, cordless base stations, ADSL modems, ISDN modems, POTS modems, etc.; *and* on all power cables (*e.g.*, from wall warts) connected to telephone-line-connected equipment; also on the handset cords of telephone sets.[11]

5. How Good is "Good Enough"?

Just to reduce the severity of a noise or RFI problem (but probably not to eliminate it), a common-mode choke should have **at least 1 kΩ (1000 ohms)** impedance at the relevant frequency. Here I refer to the magnitude of the impedance. The angle of the impedance is important only if the choke is in a transmitting antenna feedline and the magnitude of the impedance is too small, so that too much common-mode current flows through the choke and I^2R dissipation heats it.

As mentioned previously, the chief trade-off in the design of a common-mode choke is between choking impedance and power-handling ability. The next several paragraphs illustrate this point.

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[8] Old-fashioned fluorescents with iron ballasts, especially ones with neither rapid starting nor neon-lamp-based starters, are RF-quiet. New-fangled incandescents with dimmers (*e.g.*, quartz-halogen "torchiere" floor lamps) and low-voltage quartz-halogen desk lamps with solid-state transformers are very loud; these need L-C difference-mode power-line filters as well as common-mode chokes. See **Appendix 5**.

[9] See **§§ 3** and **4** above for examples. In addition, beware of variable-speed motor controls (*e.g.*, in washing machines and treadmills), electronic door-chime systems, and irrigation sprinkler control systems. In the latter systems, put a common-mode choke on every cable at the electronics box, and another at the power transformer. A switcher, as opposed to an old-fashioned iron transformer, needs chokes on both sides.

[10] Remember that RF picked up by a loudspeaker cable, which you might regard as a high-level circuit, can be coupled to a sensitive low-level stage *via* linearizing feedback circuitry in an audio power amplifier.

[11] Telephone equipment tends to be more susceptible to RFI than anything else in an American house. To cure RFI in a telephone or telephone-related device, a common-mode choke often needs to have three times the impedance needed to cure any other RFI problem. Fortunately, these are low-power and small-cable applications, so even very, very good chokes are cheap. See **Appendix 5** for examples.

Why *at least 1 kΩ?*

There are at least four ways to answer this question:

First, on the basis of experience: Much less than 1 kΩ seldom solves a problem. Too often, 1 kΩ does not. Often, you need 3 kΩ. Sometimes you need 6 kΩ.

Second, by seeing what others do: A well-known (perhaps I should say notorious) commercial common-mode-choke for 50-ohm coaxial transmission lines is Radio Works' "T-4 Line Isolator." Radio Works' performance claims for this choke are fantastic, but they are pure fantasy. Its inductance is only 21 μH; the magnitude of its impedance is only 522 Ω at 4 MHz, and it is greater than 1 kΩ for only the 10- to 21-MHz ham bands. Radio Works recommends using **two** of these chokes in a station. I tried two[12] and found them inadequate. Worse, both failed while I was transmitting less than 1500 W.[13] It was my bad experience with these chokes that motivated me to learn how to make my own.

Joe Reisert, W1JR, makes his own 50-ohm coaxial common-mode chokes by winding 12 turns of RG-303 (0.17-inch o.d., PTFE dielectric) coax on a single 2.4-inch (o.d.) ring-shaped toroid of Fair-Rite Products ferrite mix 61. The impedance of one of these chokes is about 500 Ω ohms at 3.5 MHz and greater than 1 kΩ for 7 through 30 MHz. I don't know how many of these chokes he puts in a feedline. This choke appears safe for legal-limit power if (and only if) the SWR in the transmission-line mode is low and the choke is well ventilated. With power = 1500 W, SWR = 1, and f = 28 MHz, the power dissipated in the relatively compact coaxial winding (not in the ferrite) is 10 W.

Walt Maxwell, W2DU, made a 50-ohm coaxial common-mode choke (which he called a "bead balun") by stringing a large number of ferrite beads on a straight length of coax. According to tests reported on <towertalk@contesting.com> by Tim Duffy, K3LR, the impedance of the original W2DU choke was marginal, and — worse — even with a 50-ohm resistive load (unity SWR), the choke overheated at 500 W on every band. A better bead balun was developed by WØIYH, who strung 100 ferrite beads of Fair-Rite Products mix 43, with dimensions (I *think* but I'm not certain) o.d. 0.562 in., i.d. 0.250 in., length 1.125 in. (per bead) on 10 ft.(!) of RG-142 (0.195-inch o.d., PTFE dielectric) coax. K3LR measured the impedance of one of these chokes to be:

Freq. (MHz)	**|Z|** (Ω)
1.8	1152
3.7	3483
7.1	4115
14.2	1783
21.2	1280
28.5	1234

[12] In the coaxial line from my amp. to my remote unbalanced tuner, which was followed by a 4:1 balun. One choke was at the amp. output; the other was at the tuner input, 70 ft. away.

[13] Radio Works claims that these chokes handle greater than 1500 W below 28 MHz. The chokes that I was using failed due to resistive heating of the small-diameter coaxial-cable winding by transmission-line-mode current (exacerbated by thermally insulating packaging), not due to heating of the ferrite by common-mode current. Many other failures have been reported on <towertalk@contesting.com> and <ycc@contesting.com>.

K3LR reported that the WØIYH choke got warm but did not overheat on any band at 2000 W with SWR = 1. K3LR has **three** of these chokes in each of his antenna feedlines. One choke is at the antenna feedpoint, another is at the tower-mounted antenna switch box, and another in the shack where the coax connects to the power-amplifier.

Third, by observing that it is not expensive or difficult to make and install a 1-kΩ choke, and concluding from this observation that anything less is not worth bothering with.

Fourth, by this calculation: The characteristic impedance, Z_o, of the unbalanced transmission line formed by one conductor having a circular cross-section, and parallel to an infinite horizontal ground-plane, in air, is given by

$$Z_o = 138\ \Omega \cdot \log_{10}(4h/d),$$

where h is the height of the conductor and d (<< h) is its diameter. Taking d = 0.01 m for the shield of RG-213/U coax, for h = 1 m we find Z_o= 359 Ω; and for h = 10 m, Z_o= 497 Ω. So, the impedance of a wave traveling *via* common-mode current (and voltage) on the outside of a typical coaxial cable running horizontally between 1 and 10 meters above ground is *around* 400 Ω. For the moment, to keep things simple, imagine a 400-Ω common-mode source at one end of this line, and a 400-Ω common-mode load at the other end.

Inserting a choke of impedance Z equal to 1000 Ω, purely resistive, in series with this line reduces the power flowing in common-mode to the common-mode load by a factor of $(1800/800)^2$, or 7 dB.

Seven dB of attenuation will solve some, but not most, RFI problems caused by common-mode current flowing on coax from a transmitting antenna back to the shack. Seven dB of attenuation will noticeably reduce the noise you hear due to common-mode current flowing from your house to your antenna — by slightly more than one S-unit. However, seven dB of attenuation is not likely to reduce this noise to insignificance. Moreover, …

In the real world there are standing waves in the common mode. The SWR of the common mode (not the transmission-line mode) is high, inevitably, because no one bothers to match common-mode impedances. (It would be an impossible task, because the characteristic impedance Z_o for common-mode transmission varies all over the map as the spacing between the relevant cable and return conductors varies.) This high SWR means that the impedance of a common-mode *wave* varies radically, from much less than the characteristic impedance Z_o of the *line*, to much more, in the course of a quarter wavelength on the line. The wave impedance has minima at the voltage nodes of the standing wave, and maxima at the current nodes.

If you are lucky or smart enough to insert a common-mode choke where the wave impedance is low, the effect of the choke will be magnified. If you insert a common-mode choke where the impedance is high, the effect of the choke will be minimized. If the choke's impedance is only 1000 Ω, its effect will be nil.

Bottom line: Unless you can be sure of putting it at a voltage node, you'll need much more than one 1000-Ω choke.

6. How to Make Common-Mode Chokes

This section describes how to make chokes having impedances of about 1000 Ω throughout the MF and HF ham bands. It's foolish to make anything less; and, as just discussed, it's not unusual to need 3 to 6 kΩ. To get 3 to 6 kΩ, string three to six 1-kΩ chokes in series. Do ***not*** wind/thread more turns of cable on/through the same amount of ferrite! If you did this, your choke would have much ***less*** than 1-kΩ impedance on the higher bands.

The chokes described in this section are effective for all bands from 160 through 10 meters. They are most effective for 40 m and very good for 80 and 20 m. For 160 m, their finite inductance limits their impedance. For 10 m, inter-turn capacitance limits the impedance. Their self-resonant frequencies, at which their parallel inductive and capacitive reactances have equal magnitudes, are in the neighborhood of 10 to 14 MHz. However, the resonance is very broad because the ferrite of choice is quite lossy, as discussed in **§2.1**.

If 100% of your operating is on a single band, then a choke having a sharper resonance and resonant at that band could be more cost-effective for you.[14] However, a sharply resonant choke should *not* be used in the feedline of a single-band antenna at a station that also has an antenna for another band, because (1) RF power transmitted by one antenna can return to the shack *via* common-mode on the feedline of another antenna;[15] and (2) QRN generated within your house and carried by common-mode on one feedline can be coupled to another feedline, especially if these feedlines run parallel for a way. Be-

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[14] A coil of coax on an "air" core (with no ferrite) has a fairly sharp (in other words, high-Q) resonance and can be a good choke for a single band. Ed Gilbert, WA2SRQ, has published impedance measurement data on <towertalk@contesting.com> for coiled-coax, air-core, chokes of various sizes and shapes. He found that >1 kΩ impedance could be obtained for one-octave bandwidth. However, high-Q chokes and especially air-core chokes have significant problems that a high-Z, but low-Q, ferrite-core choke does not have: (***i***) a high-Q choke must be tuned; (***ii***) an air-core choke is easily detuned by proximity to a conducting object; (***iii***) interaction between two or more high-Q chokes or other resonators, deliberate or acciden tal, in the same feedline can interact to shift the resonant frequencies; and (***iv***) a high-Q choke does not *absorb*, or *damp*, common-mode waves; it merely reflects them and redistributes the frequencies of the "normal modes" (*i.e.*, the frequencies at which the entire system resonates). For RFI suppression, it *helps* to have damping.

[15] The coupling between widely separated antennas can be surprisingly strong. (One suspects that resonances are at work.) My HF antenna is horizontal, symmetrical, balanced, in the clear, broadside to and 100 feet away from my 2-m antenna, which is vertical and also in the clear. Thus, the polarizations of these antennas appear quite orthogonal and one does not expect much cross-coupling. At each end of the coaxial feedline of each antenna is good common-mode choke. The chokes in the 2-m feedline are good not only for 144 MHz but also for HF. Yet, when I transmit high power at 14 MHz, the broadband directional coupler at the shack end of the 144-MHz feedline indicates a few watts of power. (A four-cavity, 2-m bandpass filter reflects this14-MHz power before it reaches the input of my 144-MHz receiver.) This indication occurs when I transmit on 14 MHz but not any other HF band. I suspect that my 2-m vertical antenna, in combination with the mast and lightning-safety ground below it, and coupled to the transmission-line mode of its low-loss (Heliax LDF4-50) feedline, which is terminated losslessly at 14 MHz by the 2-m filter, has a high-Q resonance at 14 MHz. I have not experimented deliberately to confirm this hypothesis, but the appearance of HF power in the 2-m feedline coincided with my installation of the 2-m filter, which would have shifted the resonant frequency. I suspect also, but again have not confirmed, that the primary mode of HF propagation to my 2-m antenna is ground-wave, guided by the soil-air interface rather than common-mode current on my feedlines or other cables.

cause I doubt that many YCCC members limit their operations to a single band, I do not discuss single-band chokes in this article.

In this **§6** I describe three kinds of choke: one appropriate for low to medium RF power on a thin cable; one for low to medium RF power on a thin cable with fat connectors attached; and one for high RF power on a thick cable. Some other designs are described in **Appendices 3, 4,** and **5**. Over time, I hope to add descriptions of still others.

I assume that you have the cable or know how to get it. Ferrite, however, is relatively hard to get — surprisingly so in view of its utility in ham radio. So I'll tell you how to buy ferrite. I'll also try to organize a group purchase of ferrite at the YCCC meeting on April 8, 2006, and *via* <yccc@contesting.com>.

6.1. How to buy ferrite

I buy surplus ferrite on eBay and at hamfests whenever I can, but these opportunities are too random and tricky to describe usefully. At a hamfest, you can see and feel what you're buying. However, seeing and feeling aren't enough because there are many ferrite mixes and you can't distinguish them without electromagnetic measurements. So I carry an HF complex-impedance bridge and wire for winding on ferrite components, to measure them. A brief description of how I do this is given in **Appendix 1**.

I buy new ferrite components in quantity from:

> Lodestone Pacific, 4769 E. Wesley Drive, Anaheim, CA 92780
> Tel. 800-694-8089 or 714-970-0900; fax 714-970-0800
> Email <sales@lodestonepacific.com>
> Web <http://www.lodestonepacific.com/>

WARNING: Lodestone Pacific is a big wholesaler, not a retailer. Do not ask them to help you figure out what you want. However, if you know exactly what you want, do not ask for information about a product, do not ask for advice, and in general do not waste their time, they will talk to you, they will be very nice, they will sell you a modest quantity, and they will even charge your credit card. Their prices are less than half, often much less than half, those of any company that advertises in *QST*.

BEFORE calling Lodestone Pacific or even looking at their website, you must be familiar with the catalog of the ferrite manufacturer, Fair-Rite Products Co. <www.fair-rite.com>. The 15th edition of this catalog, a fantastic 722-page document, is downloadable free, as an 8.2-MB PDF file, from

<http://www.fair-rite.com/newfair/pdf/15th_Edition_Fair-Rite_Catalog.pdf>.

With this catalog at hand, search the list of remainders / clearance items at Lodestone Pacific's website. You will find incredible bargains if you know what the ten-digit Fair-Rite part numbers mean and can recognize that a clearance item can be substituted for what you originally wanted.

For choking thin cables at low to medium RF power, I use:

> Fair-Rite p/n 2631102002 (a "round cable suppression core," a.k.a. "bead," of ferrite mix 31, with dimensions 1.020" o.d., 0.505" i.d., 1.125" long), unit price $ 0.9635 in the lot of 264 that I bought 3/24/2005.

For choking thick cables or thin cables with fat connectors, I use:

Fair-Rite p/n 5943003801 (a ring-shaped toroid of mix 43, 2.400" o.d., 1.400" i.d., 0.500" tall / thick), unit price $ 4.58 in the lot of 50 that I bought 3/24/2005.

6.2. Thin cable, low to medium RF power

This section describes a very simple and inexpensive choke made by threading a thin cable three times through a "binocular" core formed by two Fair-Rite p/n 2631102002, mix-31, beads side-by-side like the tubes of binoculars.

This is a cost-effective choke for any round cable of o.d. 0.2" or less, or "zip cord" of size 2 × AWG 16 or less — *e.g.*, small 120- and lower-voltage power cords, telephone cords / cables, computer cables, and coaxial cables for receiving or for transmitting HF power up to 100 W, more or less, depending on cable material and construction. The safe power limit is determined by a combination of thermal issues and the mechanical stress caused by the curvature of the cable in the choke. The radius of this curvature is about 0.5 inch.

RG-58/U coax, in which the center conductor is solid copper and the dielectric is solid polyethylene, is probably safe for 100 W in this choke. RG-58A (Belden 8259) or RG-58C (Belden 8262), in which the center conductor is *flexible* (stranded, not solid) and the dielectric is also *solid* (not foamed) polyethylene, is probably safer. In a cable having a solid center conductor, and *especially* in a cable having foamed dielectric, the center conductor is more able to mush through the dielectric and short to the shield if the center conductor is heated by too much RF current.

Manufacturers of RG-58-type cables typically specify a minimum bending radius of 2.0 inches. Subject to this bending limit, and for an ambient temperature of 40°C (104°F), RG-58-type cables are rated to carry about 500 W at 14 MHz with SWR = 1. Unfortunately, I don't know how any of these cables should be derated for sharper bending. I know only that, for a given transmitted power, the power dissipated in the center conductor is proportional to the square root of frequency; and that, for SWR > 1, the power dissipated at a maximum of the standing wave in the transmission-line-mode current is magnified by a factor of the square root of the SWR. Thus, for example, at 28 MHz with SWR = 4, the transmitted-power limit for RG-58-type cable is reduced to 175 W — *before* any allowance for bending-radius < 2.0 inches. So be careful. Don't use this common-mode choke (or any device) in a transmitting feedline where it could start a fire by shorting and arcing. Remember that polyethylene, and many cable jacket materials, are flammable.

For higher transmitted power, some hams have suggested using RG-303 (Belden 84303) coax in this choke. RG-303 has PTFE dielectric, which remains solid (although soft) up to a significantly higher temperature than polyethylene does. RG-303 also has a larger center-conductor than RG-58A or C has (AWG 18 *vs.* 20). This center conductor is solid, not stranded. However, as previously mentioned, W1JR has wound RG-303 on ferrite rings having 0.5" square cross-sections (so the inside radius of curvature of the coax would be 0.35"), and (AFAIK) he has not reported a failure at legal-limit power.

The choke described in this section would be my first choice for all kinds of small-diameter cable (including telephone cables or "cords"; serial-data, USB, FireWire, 10Base-T Ethernet and other computer cables; and low-voltage or 120-VAC power

cables or “cords”), except that most of these cables come with plugs or connectors attached that will not fit through the 0.505" hole of a number 2631102002 bead (at least, not if two passes of cable are already in the hole). However, this choke is so inexpensive that, to use it, sometimes I cut a cable and either splice it or install a new connector afterward. Splicing is not so bad if you have appropriate heat-shrink tubing.

Figure 1, below, is a photograph of one of these two-bead “binocular” chokes threaded with three turns of RG-58/U coax together with (in parallel with) a 4 × AWG 24 “indoor” telephone cable. I made this choke for W1OUN, whose remote automatic antenna tuner required two conductors for 12-VDC power and two for control.

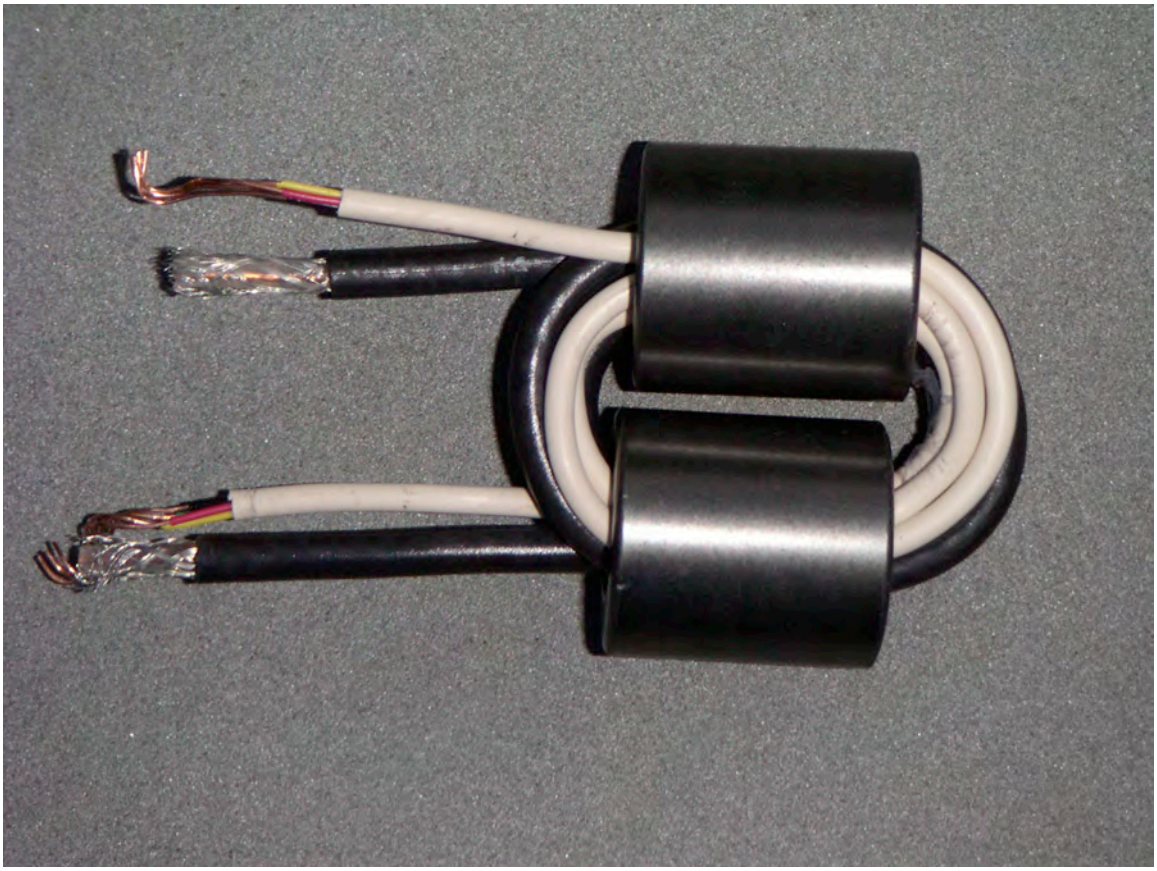


Figure 1: *Common-mode choke for the parallel combination of an RG-58/U coaxial cable and a four-wire telephone-type cable. The cables make three turns, or passes through, a “binocular” core formed by two Fair-Rite p/n 2631102002 beads. The impedance of this choke is greater than 1 kΩ from 1.8 MHz through 20 MHz.*

The magnitude of the common-mode choking impedance of this choke is greater than 1 kΩ from 1.8 MHz to 20 MHz. At 30 MHz it is 640 Ω. With just one cable (either the

coax or the telephone cable) on the same core, the impedance was 1 kΩ or greater from 1.8 MHz to 23 MHz.[16]

As previously discussed, several chokes like this one should be strung together in series to obtain sufficient common-mode choking impedance. A six-choke string that I made for W1OUN is shown in **Figure 2**.



Figure 2: *A series string of six binocular-core units like the one shown in Figure 1, on the parallel combination of an RG-58/U coaxial and a 5 × AWG 26 tuner-control cable. Three of the six unit chokes were wound with three turns; and three have 2½ turns.*

The remote-tuner power and control cable in this six-choke string has five conductors because W1OUN added a relay to his tuner. In **Figure 2** you can see that I omitted a half-turn in three of the "unit" chokes. I did this hoping to increase the choking impedance at 30 MHz, at the expense of impedance at 1.8 MHz. It's not clear that any improvement resulted. The measured impedance of a 2½-turn choke at 1.8 MHz was 700

[16] The impedance (or admittance) at the high-frequency end is limited by inter-turn capacitance, which obviously is less with thinner or fewer conductors in the winding. When winding any choke, it helps not to *cross* turns.

Ω, and I could detect no difference at 30 MHz. At 30 MHz, even 2-inch leads have significant capacitance, and my Autek VA-1 bridge[17] is at the limit of its usefulness.

6.3. Thin cable with fat connectors attached (low to medium RF power)

When a thin cable has fat plugs or connectors attached and I don't want to cut and splice the cable or install a new connector, instead of using a two beads to form a binocular core I use a single Fair-Rite p/n 5943003801, ring-shaped toroid of mix 43, 2.400" o.d., 1.400" i.d., and 0.500" tall / thick, as a core. The cost of ferrite is greater by a factor of 2.6, but the performance is almost is good, and the hole is much bigger.

For an HF choke I wind 12 to 14 turns on one of these toroids, as the thickness of the cable permits. Twelve turns is better if you care more about the high bands; 14 is better for the low bands.

Figure 3, below, shows such a choke, with 13 turns, in the low-voltage 60-Hz AC output cable (2 × AWG 20 zip cord) of the wall-wart transformer that powers my ADSL modem. Note the space between the beginning and the end of the winding. This space is necessary to reduce the capacitance between the ends, which limits the choking impedance at the highest frequencies.



Figure 3: *A wall-wart transformer for a modem, with a toroidal-core common-mode choke in its zip-cord, low-voltage, output cable. Near the other end of this cable, just before the modem, is another choke like this one.*

[17] See **Appendix 1**.

I put two such chokes in this cable. I put a string of three such chokes in the telephone-line cable connected to this modem,[18] and I put a string of binocular-core chokes in the 10Base-T Ethernet cable also connected to this modem. The telephone cable, which extends through my house and outside, passing under one end of my HF antenna on its way to the street, has several more chokes along the way. The wall-wart plugs into a multiple-outlet box with a computer and other peripherals. Additional common-mode chokes and an L-C, difference-mode, filter are in the three-conductor cable feeding 120-VAC power to this box.[19] The Ethernet cable goes to the computer and is short. Every other cable connecting this computer to the world beyond (*e.g.*, the telephone cable to its POTS modem and the telephone cables to its ISDN modem) also contains multiple chokes, at intervals.

The impedance that I measured for a single toroidal choke like the one in **Figure 3**, but having 14 turns of 2 × AWG 20 zip cord, was greater than 1 kΩ from 1.1 MHz through 26 MHz, but dropped to 340 Ω at 30 MHz.

6.4. Thick cable (including coax for high RF power)

For thicker cables of up to 0.5" diameter, *e.g.*, RG-213/U coax and 3 × AWG 14, 60-Hz-power cords, it is feasible to string enough 2631102002 beads on a straight cable to make a good choke. A string of 22 of these beads has >1 kΩ impedance from 1.8 MHz through at least 20 MHz and probably well beyond 30 MHz.[20] For sufficient choking impedance you should string more beads on the cable; *e.g.*, 110 beads would yield >5 kΩ from 1.8 to at least 20 MHz[21] and would cost about $110.

A choke having about the same common-mode choking impedance and power-handling capability in transmission-line mode as twenty-two #2631102002 beads on RG-213/U, but less vulnerable to heating by common-mode current, can be made by stacking Fair-Rite p/n 5943003801, mix-43 toroids to form a pair of “binocular” tubes each 2.400" o.d., 1.400" i.d., and 2.0" long, and threading RG-213/U through this core three and one-half times as shown in **Figure 4**. (This may be done with PL-259 connectors already attached as shown.)

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[18] See **Figure 15** in **Appendix 6**.

[19] See **Figure 10** in **Appendix 5**.

[20] As discussed in **Appendix 1**, I am not confident of my ability to measure high impedances (with magnitudes exceeding about 500 Ω) at high HF frequencies (exceeding about 20 MHz). It is especially difficult to measure such impedances meaningfully when the size of the device being measured is greater than a few inches. In the latter case, a two-plane transmission-line measurement should be made, not a two-terminal (single-plane) measurement. I am not presently equipped for two-plane measurements. However, one may extrapolate from measurements of a short string of beads. For example, the magnitude of the impedance of a 2" long by 1" wide “hairpin” of cable loaded with just two 2631102002 beads, one on each leg, as measured by my Autek VA-1 bridge, is 100 Ω at 1.8 MHz, 300 Ω at 20 MHz, and 250 Ω at 30 MHz. At this rate, 22 beads provide 2.8 kΩ at 30 MHz. **The most excellent aspect of a long string-of-beads choke is that** (if it is straight, not coiled) **one end is far from the other; so its performance is not limited by capacitance between its ends.**

[21] Compare the WØIYH choke described in **§5**. Note that RG-213/U has half the loss of RG-303 and safely handles more RF power.

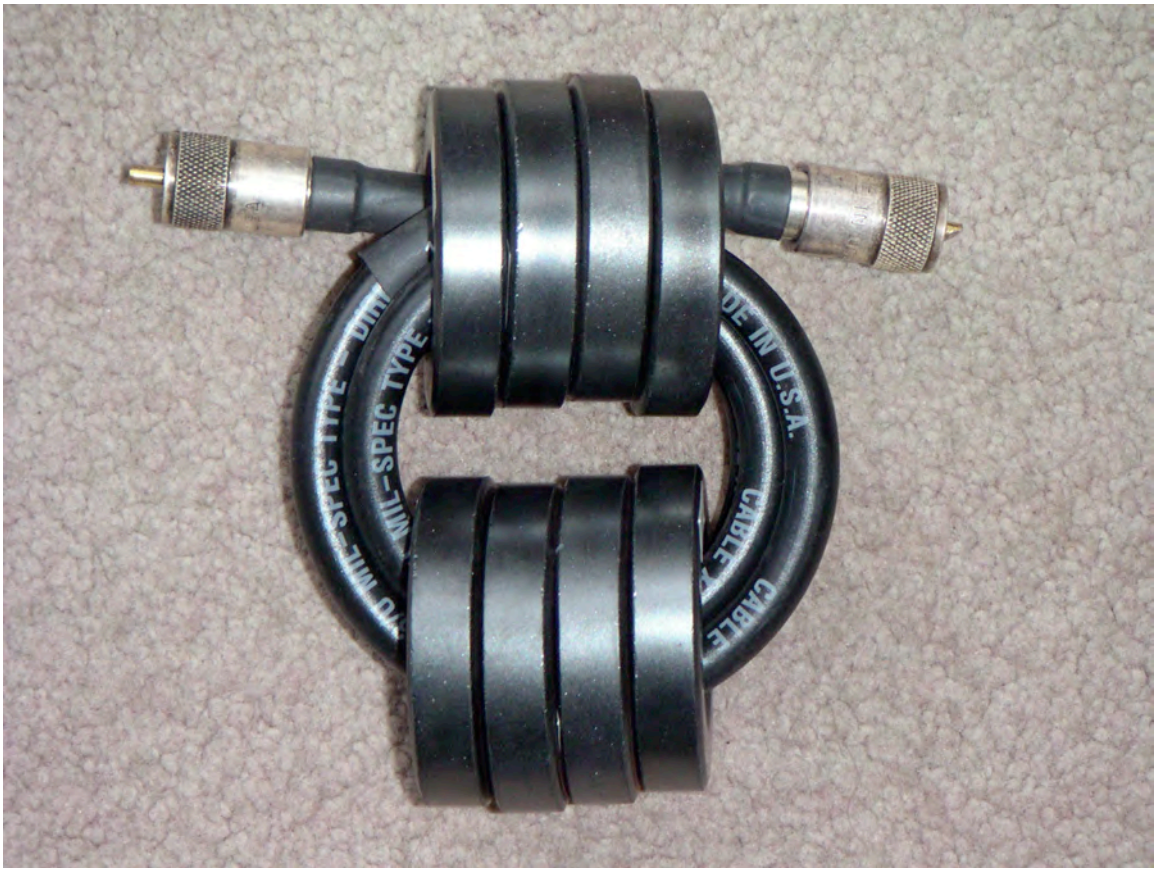


Figure 4: *Common-mode choke for high HF power, formed by passing RG-213/U coaxial cable 3½ times through a binocular core formed by two stacks of four Fair-Rite p/n 5943003801, mix-43, toroids. This choke's impedance exceeds 1 kΩ from 1.8 through 18 MHz, dropping to 550 Ω at 30 MHz. One such choke should be installed at the antenna feedpoint, one at the amplifier output, and at least one other in-between.*

The cable, whose total length is 36", passes four times through the upper tube and three times through the lower. The magnitude of the common-mode choking impedance of this choke exceeds 1 kΩ from 1.8 through about 18 MHz. At 25 MHz, I measured 700 ohms; and, at 30 MHz, 550 ohms.

By slightly loosening the turns of the coax and not requiring the toroids to be stacked as neatly as I arranged them for this picture,[22] the number of toroids can be increased to 12 and the impedance of the choke will be increased by 50% at low frequencies, but not changed much at the high end.[23]

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[22] There is no reason to stack them neatly, and there is a reason not to: the toroids should be loose so that air can circulate between them, for convective cooling. For the same reason, the turns of the cable should not be tied or taped together, and the entire assembly should not be enclosed.

[23] At my station I have just one antenna, an inverted-U doublet, for all bands 160 through 10 m. Open-wire line extends from the feedpoint of this antenna to a balanced, remote-controlled tuner. Within this tuner on the TX side is a common-mode choke comprising a bifilar winding of PTFE-insulated, AWG 10, silver-plated copper wire on a large, solid, cylindrical, ferrite core. Next, connected to the 50-Ω coaxial

6.5. Other possibilities

By presenting this handful of specific choke designs, I hope

(1) to enable hams who lack instrumentation for measuring common-mode current and/or impedance to build chokes that work better, and cost less, than commercially available chokes;

(2) to suggest issues and possibilities to hams who have instrumentation but have not experimented with common-mode chokes; and

(3) to sensitize everyone to the major issues and trade-offs relating to

(a) common-mode-choking impedance at high and low frequencies;

(b) power dissipation in the cable due to transmission-line-mode current, and in the ferrite due to common-mode current; and

(c) ferrite material and geometry.

In response to continuing questions and comments from readers I hope to revise this article to make it more useful.

The ball's in your court now.

73 de Chuck W1HIS

7. Acknowledgements

I thank all those whose feedback on the first draft of this article helped me generate this second draft. In the order that I received their comments: Fred Hopengarten K1VR, Tom Wagner N1MM, Mark Pride K1RX, Dave Jordan K1NQ, Mike Loukides W1JQ, Barry Whittemore WB1EDI, Dave Patton NN1N, Gordon Pettengill W1OUN, Jack Schuster W1WEF, Randy Thompson K5ZD, Ed Parish K1EP, Jim Reisert AD1C, George Johnson W1ZT, John Vogel N1PGA, George Harlem, Ron Rossi KK1L, Mike Gilmer N2MG, Mike Bernock N1IW, and Dave Hoaglin K1HT (who should have been a professor).

"transmitter" port of the tuner, is the solenoidal, Heliax® LDF4-50-wound choke described in **Appendix 3** and **Figure 5**. Then, a 70 ft. length of Heliax LDF5-50 runs to my shack, to two series-connected, 12-toroid, binocular-core, RG-213/U chokes like the one shown in **Figure 4**. Then there is a directional coupler, a low-pass filter, and finally the output of my amp. A 25-wire control cable for the remote tuner, which runs parallel to the LDF5-50, has several binocular-core chokes at each end. Each other (60-Hz-power, control, and exciter) cable to the amp. also has common-mode chokes. After transmitting 1500 W, CW, key-down, continuously for 10 minutes on various bands (always when the band was closed!), I have felt no warmth in the ferrite or the cable of any of these chokes, except in the ferrite of the first one, inside the tuner. (This was surplus ferrite, and I have never tried to identify it.)

Appendices

Appendix 1: Identifying Ferrite Components at a Hamfest

Barry Whittemore, WB1EDI, e-mailed me:

"I have many unknown cores that I would like to check out. Do you have a procedure? I have the following equipment available at home…: signal generator; oscilloscope; MFJ 259 antenna analyzer; …. Can it be done with this combo?"

The only time that I remember needing to characterize ferromagnetic cores professionally, I used lab-grade equipment because it was there, and more importantly because I was a kid and had to convince my boss beyond any doubt that these cores, which a big-shot MIT full-professor had developed and was pushing, were n.f.g. However, to characterize unknown cores for possible use in HF common-mode chokes, I believe that an inexpensive ham "antenna analyzer" is enough.

I use an Autek model VA-1 "HF Vector Analyzer" that I bought new for $200. It's advertised in *QST*. It was among four "high-end antenna analyzers" reviewed by Joel Hallas, W1ZR, in the May 2005 issue of *QST*. <http://www.arrl.org/members-only/prodrev/pdf/pr0505.pdf>. The Autek VA-1 is the least expensive of them, by far; but it's about as accurate as the others. Measured values of impedance are good within a few ohms or a few percent of the magnitude of the impedance, in the real or the imaginary part. The VA-1 won't indicate an impedance of magnitude greater than 1 kΩ; and its accuracy deteriorates near 1 kΩ and near its upper frequency limit, of 32 MHz.

The Autek VA-1 is also the most compact of these instruments, and the most convenient for carrying around a hamfest. It fits in a jacket pocket and is self-contained, powered by an internal 9-V battery. It includes a signal generator (an oscillator that is continuously tunable from slightly below 0.5 MHz to above 32 MHz in several overlapping ranges); a digital frequency-counter and $3\frac{1}{2}$-digit display; a bridge for measuring both the real (resistance, R) and the imaginary (reactance, X) parts of the complex impedance ($Z = R + iX$) of an unknown two-terminal device; and a "PIC" microprocessor programmed to convert raw measurements and display them as R, X, and |Z| in ohms; the angle of Z in degrees; and several other derived quantities including inductance (L), capacitance (C), SWR in a 50-ohm (or other) system, and cable loss. This instrument, unlike the MFJ-269 and others, determines and displays the sign of X, and the sign of the angle of Z. Thus, it can tell an inductor from a capacitor.

Unfortunately, this and all similarly compact and inexpensive instruments are vulnerable to RFI because their bridge detectors are untuned. Therefore, they can't directly measure the impedance of an HF antenna system that's near an AM broadcast station. However, for measuring a small component like a ferrite core wound with one turn or a few turns of wire, they're fine.

So I replied to Barry:

"Yes. You should be able do it with just the MFJ 259 antenna analyzer.

“Wind one turn of insulated hookup wire on the unknown core, or a few turns, depending on the size of the core. (See the examples below.) You want the magnitude of the impedance of this winding to be in the range that the analyzer can measure reasonably accurately -- between about 10 and 250 ohms. Keep the leads as short at possible, and keep everything away from conducting surfaces like steel desk tops.

“Log all of your measurements as you go. Archive them in your computer.

“Measure Z (both the real and the imaginary parts; or, equivalently, the magnitude and the angle) starting at the lowest possible frequency (0.5 MHz for my Autek model VA-1, HF "Vector Analyzer"). At this low frequency, Z should be nearly purely inductive; in other words, its angle should be nearly equal to plus 90 degrees; in other words, the real part of Z should be near zero.

“Next, measure Z at double the previous frequency. If the ferrite is nearly lossless at these frequencies, the magnitude of Z will be twice what it was before, and the angle will still be +90 deg. OTOH, if the ferrite is lossy, |Z| will have less than doubled; and the angle will be further below 90 deg.

“Keep increasing the frequency and note where the magnitude of Z stops increasing in proportion to frequency, or stops increasing and starts decreasing. (Beyond the latter frequency, the angle of Z may be negative.)

“Measure Z all the way to 30 MHz.

“What you're after can almost be summed up by just two derived values: (1) for sufficiently low frequencies, the inductance of a winding having a given number of turns; and (2) the Q of this inductor (*i.e.*, the ratio of its inductive reactance to its equivalent series resistance) at a frequency of interest (*e.g.*, 7 or 14 MHz). A third interesting value, related to these two, is the frequency at which the Q drops to 1. This is the frequency where the angle of the impedance drops to 45 degrees. You probably won't want to use the ferrite much above this frequency.

“At sufficiently low frequencies where the impedance is nearly purely inductive (and inter-turn capacitance is negligible), the inductance is proportional to the square of the number or turns in the winding. In manufacturer's data sheets, you will see values for ‘inductance per square turn’ or ‘inductance per turn squared.’

“Match your measurement data with the curves and tabular data in the Fair-Rite Products catalog for parts having the same dimensions. The differences between ferrite ‘mixes’ can be dramatic. Of course your goal is to determine not the Fair-Rite mix number, but the impedance that a choke will have. Mainly you want the magnitude of this impedance to be great enough. *If* the choke will be on a transmitting antenna feedline and the magnitude of the choking impedance might not be enough, then you need the resistive (real) part of the impedance to be small, so common-mode current doesn’t overheat the ferrite.

However, for RFI suppression away from the antenna, a high resistive part is OK.

“I label ferrite parts and store them in containers labeled with an equivalent Fair-Rite mix number. Mixes 31, 43, 61, and 77 are common.

“You will find parts, such as toroids, that look to the eye like they might be ferrite; but, when you measure them, it's obvious that they are not like any ferrite you’ve ever heard of. There are a lot of powdered-iron cores out there. Sometimes but not always you can recognize them because they are painted. (There are color codes for powdered iron cores.) I have yet to find a powdered-iron core that was useful in an HF common-mode choke. Mostly, their magnetic permeabilities are too low. This is glaringly obvious when you measure, say, a three-turn winding and can't see the difference between having the winding on the toroid, or having it in thin air.

“A ferrite mix like number 77, which is good in transformer cores of switching power supplies and for RFI suppression at MF, has higher magnetic permeability and yields higher inductance per square turn at frequencies well below 1 MHz, than a ferrite made for RFI suppression at HF (*e.g.*, mix 31) or VHF (*e.g.*, mix 43). On the other hand, mix 61 shows less inductive reactance and much, much less resistance (virtually zero) in the low HF range, than mixes 31, 43, or 77. (Mix 61 is what I use in QRO, HF, balun transformers.)

“Here are a few illustrative examples of impedance measurement data picked at random from my archive:

“1. Ten identified, Fair-Rite p/n 2643801202, mix 43, toroids strung like beads on a few inches of wire:

Freq. (MHz)	Impedance ohms	deg
1.0	43	78
3.5	136	75
7.0	230	66
14.0	366	55
21.0	426	46
28.0	443	37

“Note that this ferrite (mix 43) shows some loss (angle of Z < 90 deg) at 1 MHz, and becomes increasingly lossy (the angle decreases) as f increases from 1 to 30 MHz. The magnitude of the impedance of this one-turn ‘winding,’ or pass, through ten toroids appears to have topped out by 30 MHz. Note that the measurement accuracy of my Autek VA-1 for impedances with magnitudes above 250 ohms, especially at the high end of its frequency range, may be poor.

“2. One ‘turn’ on (*i.e.*, one pass through) a Fair-Rite mix-43, split-bead, ‘Cable Snap-it™’ about 1.25 inch long by about 3/4 inch square, able to fit around a cable of diameter up to 1/4 inch. Radio Shack sells these, and many are found at hamfests.

Freq. (MHz)	|Z| (ohms)
3.5	40
14	115
28	171

"There is no angle data here; but note that the variation of |Z| as a function of f here is similar to that seen above for the string of mix-43 toroids.[24]

"3. One Fair-Rite p/n 0431173551 "Snap-it," also mix 43, but with i.d. equal to 0.75" (for THICK cable), clamped around a single loop of wire 6" long:

Freq. (MHz)	|Z| (ohms)	Angle (deg)
1.0	20	55
10.0	79	52
20.0	113	60

"Here, the wire loop was much too long, so its inductance even in open air, without the ferrite, was significant: 21 ohms purely inductive at 10 MHz. This significant, pure-imaginary, impedance added to the Z of the ferrite part and confused things. The ferrite part appeared to have higher Q at 20 MHz than it really did. I included this example to illustrate the importance of keeping leads short. If in doubt, measure the 'winding' without the core.

"4. One Fair-Rite p/n 5943003801 toroid (mix 43) wound with 5 turns, which was too many for the immediate purpose. |Z| was so high that winding inter-turn capacitance was not negligible.

Freq. (MHz)	|Z| (ohms)	Angle of Z (deg)	
3.5	332		
14.0	235	8	(nearly purely resistive)
28.0	203	18	(ditto; note that |Z| is past its peak, suggesting that parallel-LC resonance has been passed)

[24] To get 1 kΩ at 3.5 MHz you would have to string 25 of these split-bead 'Snap-its' on a cable. This would *not* be cost-effective. Snap-its are convenient but *very* expensive. For less than the cost of one Snap-it, you could get 1 kΩ at 3.5 MHz using only *eight* p/n 2643801202 toroids in two stacks of four to make a binocular core, and passing the same cable three times through this core. (The hole is big enough.) Better yet: use just two of the mix-31 beads that I recommend in this article. The cost is about the same but the choke is better both at lower frequencies and at higher frequencies.

"5. One unknown bead, o.d. 0.685", i.d. 0.375", length 1.125", from a lot of 324 found at a hamfest, wound with two turns of wire (*i.e.*, two passes through the hole):

"Freq. | |Z| | Angle
(MHz) | (ohms) | (deg)
------+--------+--------
1 | 37 | 71
2 | 83 | 77
5 | 150 | 76
10 | 271 | 64
20 | 414 | 57

"Within the precision of the measurements, this looked like mix 43 to me.

"Incidentally, ferrite mix 77 looks very much like mix 43 within the HF range. To distinguish them easily you must measure below 1 MHz, where you'll see that mix 77 provides much greater Z, or inductance per square turn.

"6. And now something that does _not_ look like mix 43 within the HF range: a 2.4"-diameter toroid of Fair-Rite mix 61, wound with five turns:

"Freq.| |Z| | Angle |
(MHz)|(ohms)| (deg) |
-----+------+-------+
3.5 | 114 | 90 | <-- Pure inductance!
14.0 | 477 | 76 |
28.0 | 584 | 54 | <-- Contrast with the mix-43 toroid above!

"You can see why I use mix 61 in an HF QRO balun. You can also see why I would not use it in a common-mode choke for the low bands."

Appendix 2: Noise Sniffing

WATCH THIS SPACE FOR: Description and photo of shielded B-field sensing loop; how to utilize. Description and photo of calibrated RF current transformer. Circuit-breaker flipping; anomalous observations. Conversion of QRN on the 60-Hz power line from difference-mode to common-mode by the RF-imbalance of household circuits (only the hot side of the line is switched). Utilizing shunt C to exclude difference-mode QRN from your house. Utilizing L-C difference-mode filters to contain difference-mode QRN generated by household lamps and appliances.

Appendix 3: The Mother of All Coaxial Common-Mode Chokes

I was afraid to put a choke like the one shown in **Figure 4**, wound with RG-213/U coax, in the part of my coaxial feedline that runs through the attic of my house, where I would not notice if it overheated until possibly too late. So, in that part of the line I inserted a common-mode choke that I made by winding Heliax® LDF4-50 semi-rigid coax on a cylindrical core containing 15 lbs. of ferrite. This choke is shown in **Figure 5**.

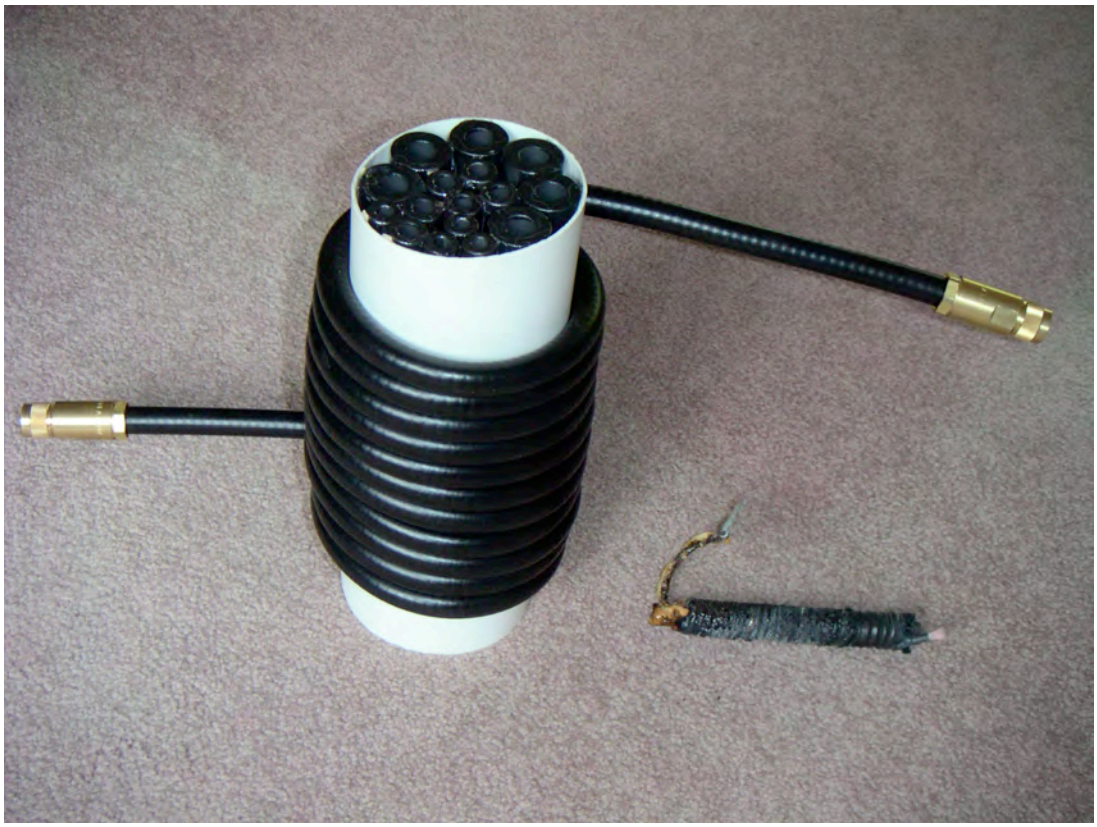


Figure 5: *At upper left, a coaxial common-mode choke made by winding Heliax® LDF4-50 semi-rigid coax on a cylindrical core containing 15 lbs. of ferrite beads. At lower right, the charred remains of a Radio Works T-4 Line Isolator like the one that the Heliax-wound choke replaced.*

The inductance of this choke is 45 μH. Its impedance is 665 Ω, purely inductive, at 2 MHz. The magnitude of the impedance exceeds 1 kΩ from 3.5 through about 10 MHz; it drops to 550 Ω (nearly capacitive) at 16 MHz and 245 Ω (capacitive) at 32 MHz. As previously mentioned, I am unsure of my ability to measure high impedances at higher HF frequencies. I am especially unsure when the size of the device being measured is as large as this one. Still, because this choke might need help at higher frequencies, I loaded a few feet of coax on either side of this choke with large-diameter ferrite Snap-its.[25]

[25] See Appendix 1 and the previous footnote.

Appendix 4: A "4:1 Current Balun"

A common-mode choke is sometimes called a "1:1 balun," and sometimes a "1:1 current balun." The longer name has three parts: (*i*) "**1:1**"; (*ii*) "**current**"; and (*iii*) "**balun**." In this Appendix I will explain each part. Then I will show how to make a useful device known as a "4:1 current balun."

The "**1:1**" in "1:1 balun" or "1:1 current balun" signifies that the ratio of the difference-mode current at the input of the device, to the difference-mode current at the output of the device, is one-to-one. The ratio of the difference-mode voltage at the input of the device to the difference-mode voltage at the output is also one-to-one. Thus, **an ideal common-mode choke is equivalent to an ideal 1:1 transformer**, *i.e.*, an ideal transformer whose secondary-to-primary turns ratio is unity.

A common-mode choke is also like a transformer in that, ideally, **common-mode current can not flow between the input** (the primary winding of a transformer) **and the output** (the secondary winding of a transformer). Relatedly, the input is isolated from the output with respect to common-mode *voltage.*

Thus, a common-mode choke or, equivalently, a 1:1 transformer can transfer power from a source that is unbalanced with respect to ground (*e.g.*, a transmitter with a 50-ohm coaxial output) to a load that is balanced with respect to ground (*e.g.*, a center-fed horizontal dipole antenna with 50-ohm feedpoint impedance) without driving common-mode current into the load or raising its common-mode voltage with respect to ground.

A transformer that connects a balanced load to an unbalanced source while isolating the load from the source in common-mode is called a "balun" transformer or simply a "**balun**." The word "balun," obviously, is formed from the first syllables of the words "balanced" and "unbalanced."

A balun transformer may have a secondary-to-primary turns ratio different from unity, either less than one (in a step-down transformer) or greater than one (in a step-up transformer). A "4:1 balun" has a secondary-to-primary turns ratio equal to 2. It steps voltage up, from the primary (unbalanced) side to the secondary (balanced) side, by a factor of 2. It steps current down by a factor of 2. It steps impedance up by a factor or 4. The "**4:1**" in the name is the **impedance ratio**.

I have explained (*i*) the "1:1" or "4:1" part, and (*iii*) the "balun" part, of the name "1:1 current balun" or "4:1 current balun"; but I have not yet explained (*ii*) the "current" part. The meaning of this part of the name is not so obvious. This part is meaningful when (and only when) the impedance ratio is not 1:1. To explain its meaning, I'll use the "4:1 current balun" as an example. The extension to other ratios, *e.g.*, to a "9:1 current balun," will be obvious.

Two very different devices are known as "4:1 baluns." One is the "4:1 current balun." The other device is the "4:1 voltage balun."

An ideal "**4:1 current balun**" is equivalent to an ideal **transformer having separate secondary and primary windings**, insulated from one another, and having a 2:1 turns ratio. Common-mode current cannot flow through an ideal 4:1 current balun. A good current balun (4:1, 1:1, whatever) acts as a common-mode choke.

An ideal "**4:1 voltage balun**" is equivalent to an ideal **autotransformer** having **a single, center-tapped winding**. Common-mode current **can** flow through an ideal 4:1 current balun. Common-mode current **does** flow through a 4:1 current balun if the load has any imbalance.

Every "4:1 balun" that I have seen in a commercial antenna tuner has been a voltage balun. If you use such a tuner with a balanced transmission line to feed an antenna that is not very well balanced, then you have a common-mode current problem. Your received SNR is being reduced by household noise traveling out the transmission line and coupling into the differential, receiving mode of the antenna. You may also notice RF in the shack.

The antenna will not be balanced if the feedline is not perpendicular to the antenna, if it is not level, if the ground slopes beneath it, or if other conductors are not positioned symmetrically with respect to its bisecting plane. A common-mode choke in the coax between the transmitter/amp and the tuner will help, but will leave the case of the tuner "hot" with RF. Separately grounding the case of the tuner will defeat the purpose of the common-mode choke.

A better solution is to replace the 4:1 voltage balun with a 4:1 current balun.

Figure 6 (on the next page) shows the 4:1 current balun that I made to replace the 4:1 voltage balun in my Heathkit model SA-2500 autotuner. This balun transforms a 50-Ω, unbalanced, coaxial input to a 200-Ω balanced output. The load impedance may differ substantially from 200 Ω resistive, in which case one-quarter of this load impedance appears at the input (retarded by the *ca*. 8-ft. length of transmission line within the balun). Although the current and voltage stresses on the balun are increased by a factor of the square root of the SWR, this balun is designed to be indestructible at legal-limit power. I calculated that it could handle 15 kW with SWR = 1, and 1.5 kW with SWR = 100. However, I have not been able to test it at these limits. ☺

The balun is built in an aluminum box with a Teflon/gold SO-239 connector on one face and a pair of steatite feedthrough insulators on the opposite face. The bottom of the box is lined with ceramic tile 3/8" thick. Six bifilar-wound toroids, standing on edge, are set in blobs of RTV on the tile.

The circuit comprises two identical bifilar transmission lines, each having 100-Ω characteristic impedance and loaded with a string of three identical, toroidal, ferrite, common-mode chokes. At one end, these transmission lines are connected in parallel to the 50-Ω coaxial connector. At the other end, these transmission lines are connected in series to the 200-Ω balanced output terminals. Connecting the 100-Ω lines in parallel matches the 50-ohm input impedance; and connecting them in series matches the 200-ohm output impedance.

Each of the six ferrite toroidal-core chokes is wound with seven turns of the bifilar transmission line. Each ferrite toroid is a Fair-Rite Products p/n 5961003801 (mix 61).

Each 100-Ω transmission line comprises a pair of AWG 10, stranded, silver-plated copper wires insulated with two layers of Teflon. I started with wire having insulation thickness equal to 0.016", and sleeved this wire with Teflon tubing having wall thickness

equal to 0.020". The o.d. of the tubing was 0.1875". Small strips of Scotch glass-fiber adhesive tape at intervals of about 3" hold the two insulated conductors together. The characteristic impedance of this transmission line, as wound on the toroids, measured by an HP network analyzer, was 95 Ω. My Autek bridge (*cf.* Appendix 1) indicated 105 Ω.



Figure 6: *Homebrew 4:1 current balun for 160 through 10 meters, built to handle 15 kW with SWR = 1, and 1.5 kW with SWR = 100.*

The inductance of the winding of one toroidal choke is 25μH; for three in series, 75 μH.

With a 203-Ω resistor connected to the output terminals, I measured the input impedance of the balun with the Autek bridge. The results were:

Freq. (MHz)	(ohms) R	X	SWR
1.75	52	5	1.10
3.5	54	-1	1.08
7.0	54	-1	1.08
14.0	60	0	1.20
28.0	48	4	1.08

The uncertainties of measurements by the Autek bridge are of the order of a few ohms in R and in X, so I would not try to read much into the departures from (50 +*i*0) Ω.

I was unable to measure the transmission loss through the balun. It was too small. My *estimate* of the power loss in the balun due to wire resistance was 0.5% at (IIRC) 7 MHz. I was unable to feel any warmth in either the windings or the cores of the balun after 15 minutes of transmitting 3 kW, CW, at 100% duty, through the balun into a water-cooled dummy load.

Appendix 5: Difference-Mode 60-Hz Power Line Filters

It is necessary to put difference-mode, L-C, EMI filters between certain types of lamps and household appliances and the 60-Hz power line, because these lamps / appliances generate powerful difference-mode QRN. If this QRN is allowed to get onto the 60-Hz power line, then a substantial fraction of it will be converted from difference-mode to common-mode because the power line is highly unbalanced for RF. (The chief cause of this imbalance may be the practice of switching only the "hot" sides of circuits.)

In my house, some of the worst difference-mode QRN generators are cheap Chinese-made torchiere lamps from Home Depot. These lamps have 300-W, quartz-halogen, tubular, incandescent lamps and solid-state dimmers. The dimmers are very short on RF filtering. A Corcom type 10VR3, two-stage, L-C, difference-mode, EMI filter mounted on the base of the lamps eliminates the QRN very nicely. The filter is grounded to the metal body of the lamp, which serves as a shield to contain the QRN. **Figure 7** shows one of these filters.

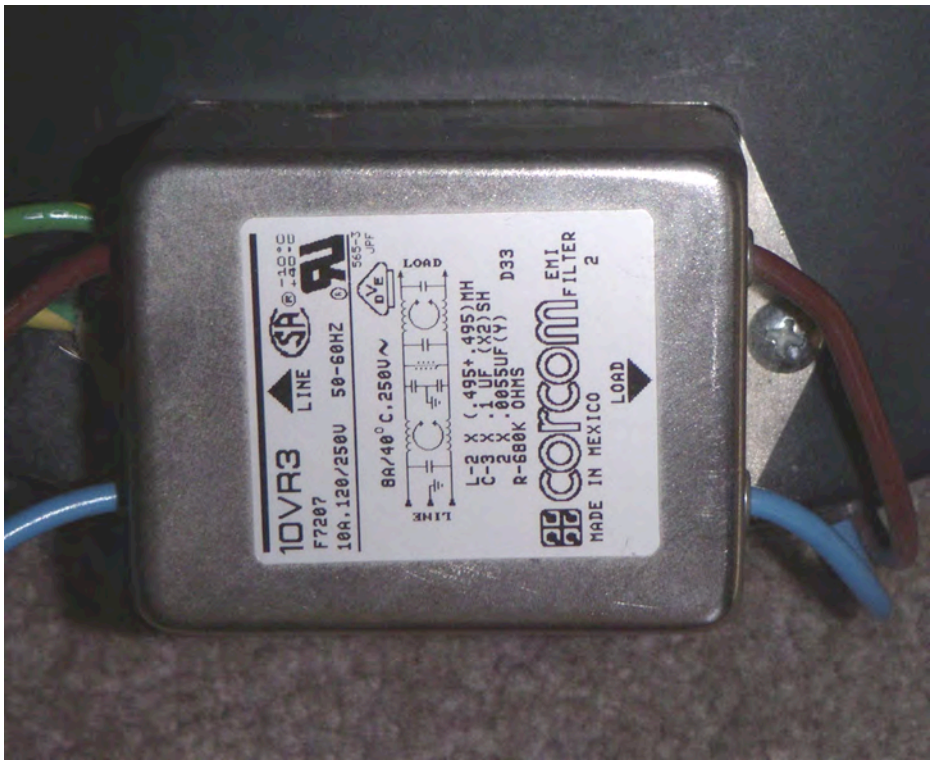


Figure 7: *Corcom difference-mode EMI filter on base of QRN-generating lamp.*

Two-stage filters like the one shown in **Figure 7** are expensive, but many single-stage Corcom and Potter-brand, difference-mode, AC-line filters show up at hamfests at prices of $2 to $5. **Figure 8** shows two examples.

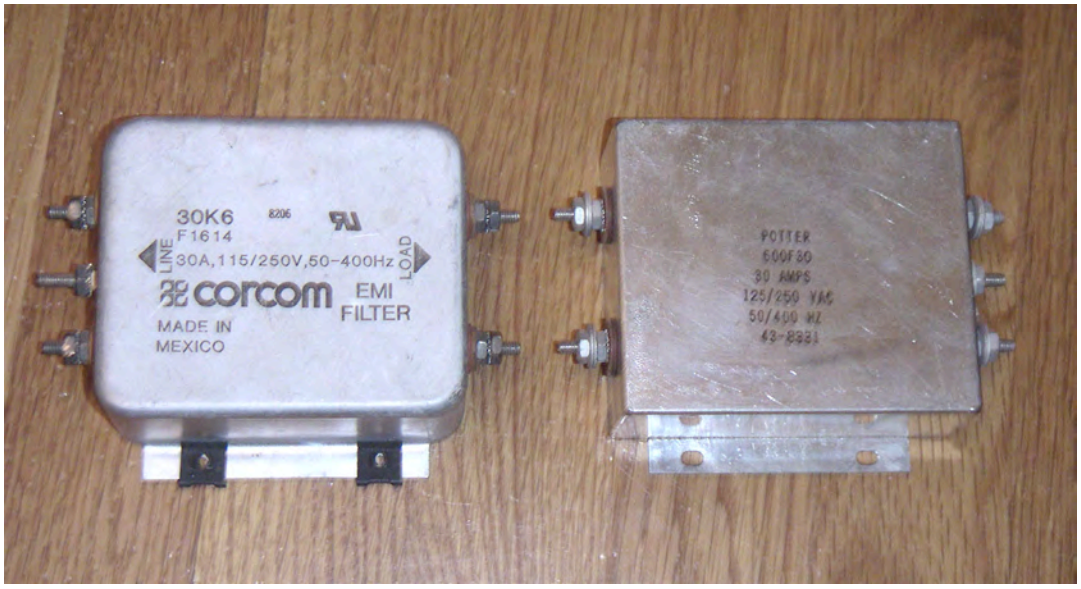


Figure 8: *Corcom and Potter, 30-A, 115/250-VAC, difference-mode, EMI filters bought at hamfests for $5 each.*

Duplex- and multiple-outlet boxes with difference-mode EMI filters built-in also show up at hamfests. **Figures 9** and **10** show two examples.



Figure 9: *Potter 12-A, 115-VAC, difference-mode EMI filter in box with duplex outlet, bought at hamfest for $10. (Ferrite toroid on line cord not included.)*



Figure 10: *15-A, 120-VAC, multiple-outlet box including difference-mode EMI filter, fuse, switches, and surge protectors. The toroidal- and two binocular-core ferrite common-mode chokes were added to the line cord.*

I have added two-stage Corcom 10VR difference-mode filters and ferrite-bead common-mode filters to many cheap (typically $2 to $2.50) multiple-outlet strips like the one shown in **Figure 11**.



Figure 11: *15-A, 120-VAC, multiple-outlet strip with Corcom two-stage, L-C, difference-mode EMI filter and ferrite-bead common-mode choke added.*

An excellent two-stage, L-C, difference-mode, 7-A, 120-VAC line filter is made by W3NQN and sold by Array Solutions <http://www.arraysolutions.com/Products/nqnaclinefilter.htm>. Figure 12 shows one of these filters.



Figure 12: *7-A, 115-VAC, two-stage, L-C, difference-mode EMI filter by W3NQN, with ferrite-toroid and -bead common-mode chokes added.*

Appendix 6: More Common-Mode Chokes

Figures 9 through **12** in **Appendix 5** show common-mode chokes as well as difference-mode L-C filters, because many (not all[26]) QRN sources that are fundamentally difference-mode generators are *themselves* sufficiently unbalanced for RF and have sufficient size that, even if the difference mode were completely contained, significant common-mode QRN would be injected into the AC power line.

In this **Appendix 6**, several other common-mode chokes are described. **Figure 13** shows a binocular-core choke similar to that of **Figure 4**, but for a large, 2 × AWG 4, DC power cable.

[26] The metal-bodied torchiere lamps with Corcom difference-mode filters attached as discussed above, do not require common-mode chokes. This exception is remarkable because, without the excellent two-stage Corcom filters, these lamps are fierce QRN sources.



Figure 13: *Common-mode choke for a 2 × AWG 4, DC power cable, formed by threading the cable 3½ times through a binocular core formed by two stacks of five Fair-Rite p/n 5943003801, mix-43, "ring" toroids.*

Figure 14 shows common-mode chokes formed by stringing ferrite toroids like beads on two 3-conductor, 240-VAC cables, one for 60 A and one for 40 A, leaving the main circuit-breaker panel in the basement of my house. The 60-A cable feeds a sub-panel from which two 120-VAC, 15-A circuits and one 240-VAC, 30-A branch circuit feed my ham shack. The 40-A cable does not go to my shack, but it runs close and parallel to the 60-A cable for some distance, so it is coupled to the 60-A cable at radio frequencies.



Figure 14: *Common-mode chokes formed by stringing ferrite toroids like beads on two 3-conductor, 240-VAC power cables, one 60-A and one 40-A.*

Every branch circuit leaving the 60-A sub-panel is individually choked; and the circuits feeding my shack also have difference-mode, L-C filters.

Telephone and computer-network cables run between three sets of four RJ-11 jacks: one set in my ham shack on the second floor; one set at my wife's computer on the first floor; and one set near the utility service entrance in the basement. Common-mode chokes are on the cables between these sets of jacks, and on every cable plugged into any jack. **Figure 15** shows some of the latter chokes.

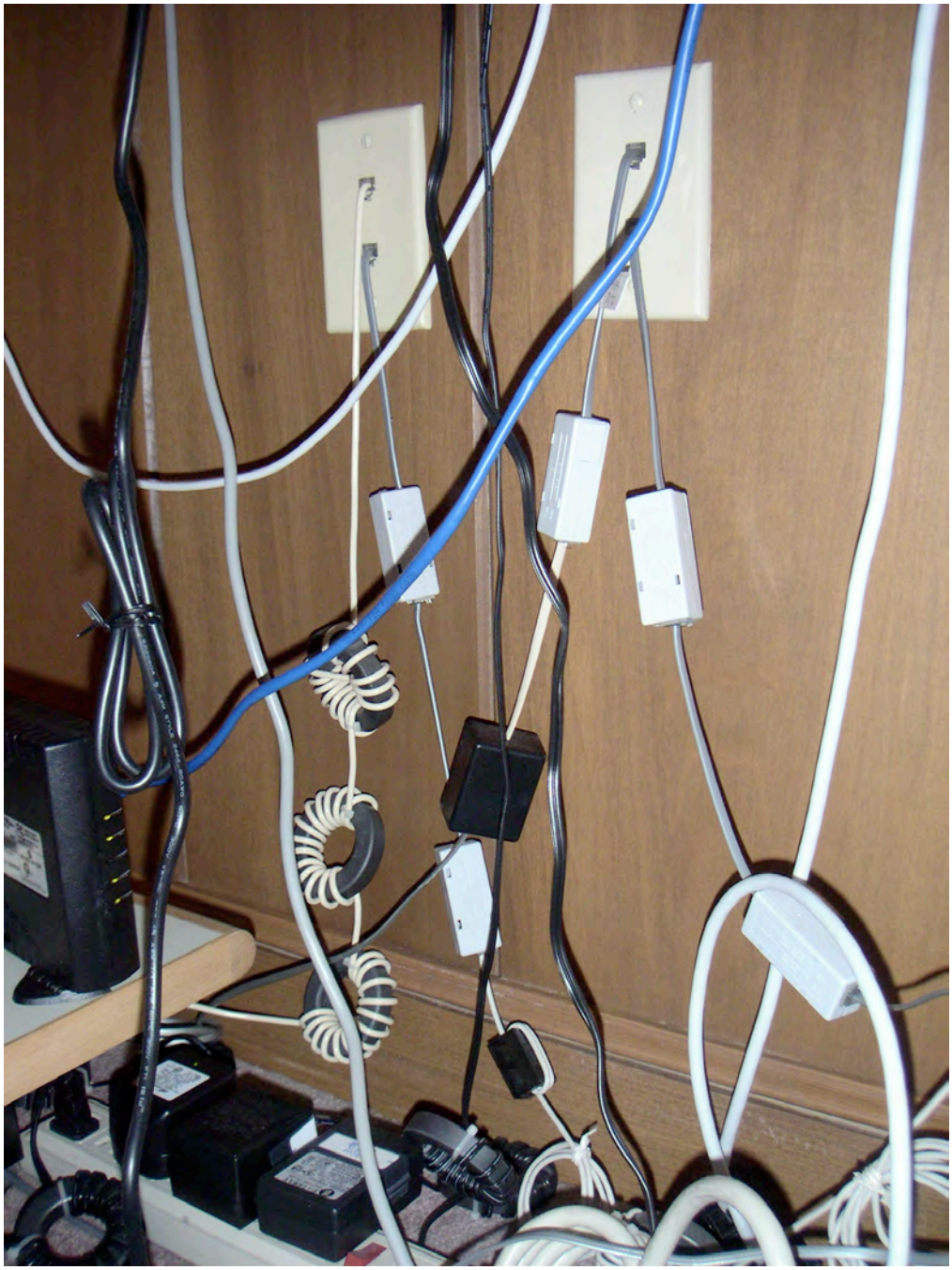


Figure 15: *Common-mode chokes on telephone and computer cables plugged into four wall jacks behind my wife's computer. On the cable plugged into the upper left jack are three chokes wound on 2.4-inch o.d., Fair-Rite p/n 5943003801, ring-shaped toroids of ferrite mix 43. (Compare* ***Figure 3****.) On the cable plugged into the lower left jack are two K-COM modular chokes and one home-brew, three-turn, bead choke. On the cable plugged into the upper right jack are one K-COM and one K-Y modular choke. On the cable plugged into the lower right jack are two K-COM chokes. Also visible, at the bottom of the picture, are three 5943003801 toroidal chokes on power cables.*

Some of these chokes are packaged, “modular” common-mode chokes from K-COM <http://www.k-comfilters.com>. Although these devices are advertised as “filters,” they are common-mode chokes, made by winding a bundle of four insulated magnet-wire conductors on a small ferrite toroidal core. They are available for four frequency ranges. The ones made for HF have impedances exceeding 1 kΩ from 1 through 30 MHz. The two-wire version costs $17 and the two-wire version costs $23.

The choke packaged in a black, nearly cubical box is from KI6KY’s firm K-Y FILTERS <http://www.ky-filters.com>. This is also a common-mode choke comprising a multifilar winding on a small ferrite toroid. However, this is a series string of two toroidal chokes; and its impedance is substantially higher than that of a K-COM choke. The two-wire, HF version costs $25.

The K-COM and K-Y chokes have RJ-11 modular plugs and jacks, and are quick and convenient to install. The K-Y choke is more effective. One K-Y choke usually works where two K-COM chokes would be required, and costs less than two K-COM chokes would. However, the same common-mode impedance can be gotten less expensively by rolling your own chokes.

No amount of common-mode choking impedance in the telephone line cord is sufficient to eliminate RFI in some (fairly many) telephone sets. It is necessary also to insert a common-mode choke in the handset cord (the “coil cord”) where it enters the base of the telephone. K-COM makes a modular four-wire common-mode choke with the smaller connectors used with a handset cord. **Figure 16** (next page) shows one of these chokes installed on our kitchen telephone, which required it.



Figure 16: *K-COM modular four-wire common-mode choke on the handset cord, and K-Y modular two-wire common-mode choke on the line cord, of our kitchen telephone. Also visible, through the transparent plastic telephone stand, are a home-brew 5943003801 toroidal choke on the low-voltage power cable, and a four-bead binocular-core choke on the telephone line cable, of a Caller-ID box.*

In this Figure, two telephone-line chokes and one power-cable chokes are also visible.

Figure 17 shows two more common-mode chokes in power cables.

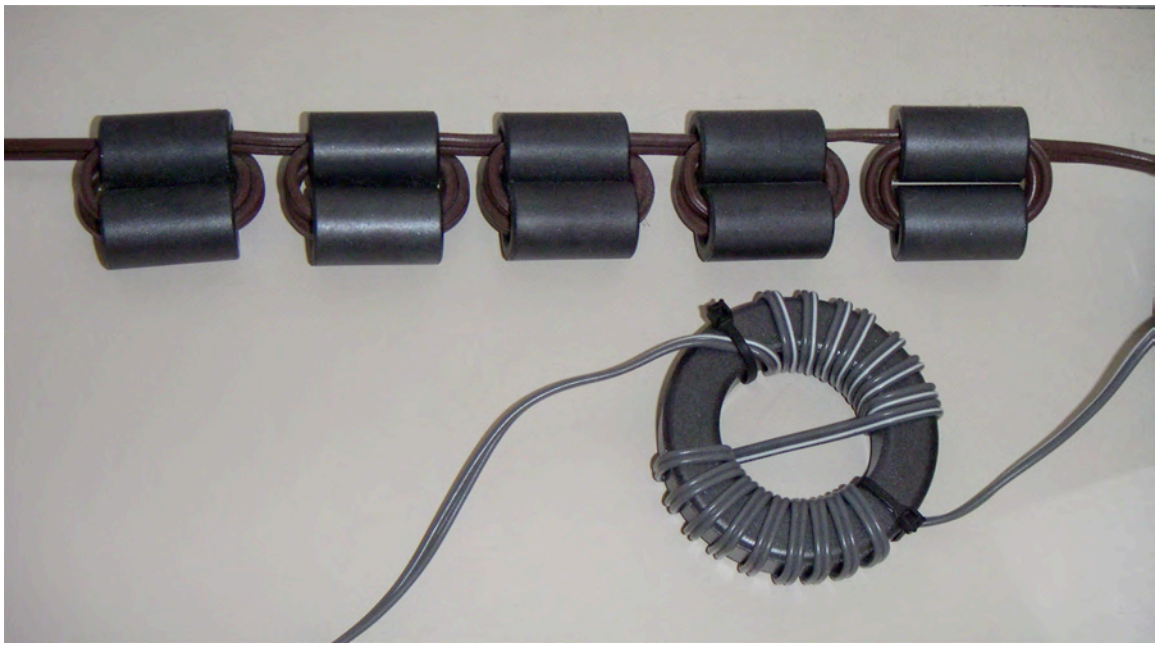


Figure 17*. Above, a common-mode choke in the 2 × AWG 18 zip-cord of a 120-VAC, 6-A, extension cord. This is a series string of five binocular cores each wound with 2 ½ turns. Below, a common-mode choke in the thin, 2 × AWG 24, zip-cord of a wall wart. This is a 5943003801 toroid wound with 17 turns. The winding is split to increase the separation between its ends, to reduce capacitance and improve high-frequency performance. In practice, the improvement is slight.*

Yet another arrangement of common-mode chokes in power cables is shown in **Figure 18**. In this case, the power cables are two 3 × AWG 12 and two 3 × AWG 14 "Romex" type cables for 120-VAC, 20-A and 15-A branch circuits leaving the aforementioned distribution sub-panel near my ham shack. As mentioned, every branch circuit leaving this panel has a common-mode choke. There was room to install chokes for most of the circuits inside the large metal box behind the panel. For a few circuits, the chokes had to be installed outside. To make room for the latter chokes I stacked two square junction boxes atop an existing box, from which the four Romex cables emerged.

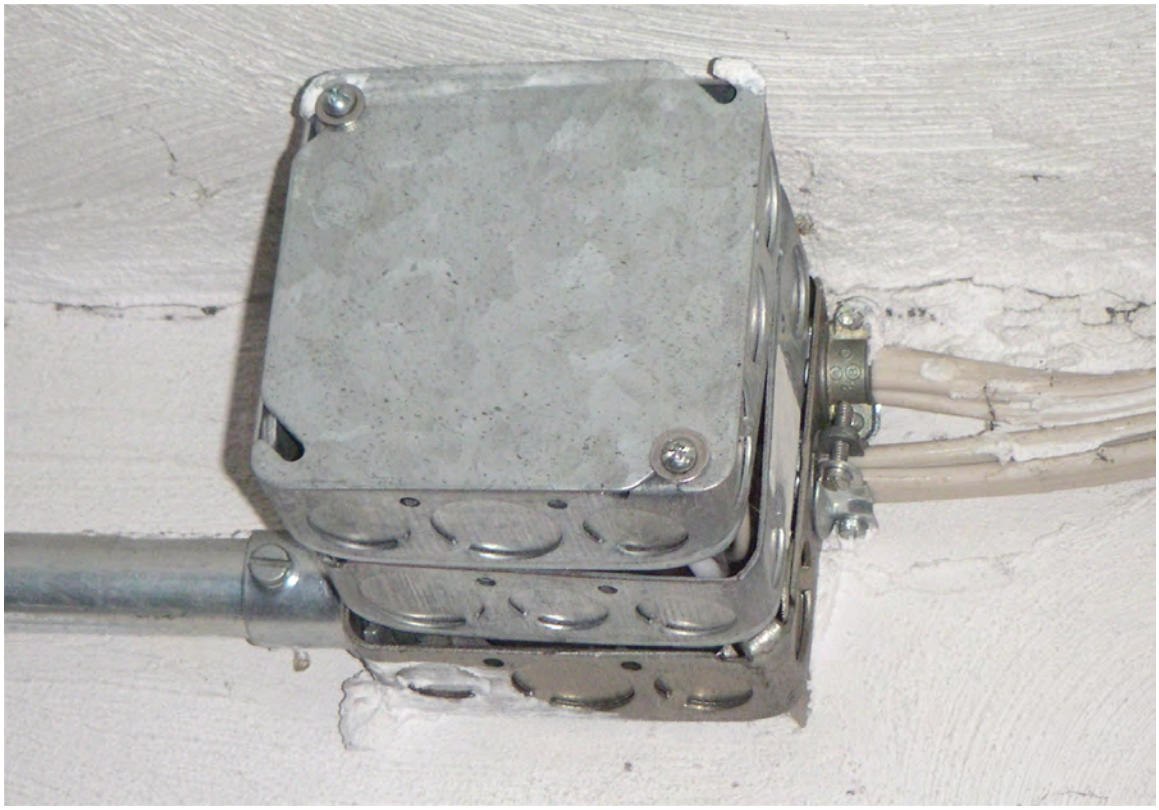


Figure 18. *Stacking two additional square junction boxes atop an existing one created room to install common-mode chokes on the four Romex-cables seen at right. Each choke was a 5943003801 toroid wound with three insulated AWG 12 or 14 wires (matching the wire gauges of the respective Romex cables). Connections were made with standard wire nuts.*