Broadband Receiving Antenna Matching

Mark Connelly, WA1ION – 15 July, 2003

This article addresses the subject of obtaining the best signal transfer from an antenna to the typical 50-ohm receiver input over a wide frequency range, with emphasis on medium-wave (500 – 2000 kHz), encompassing the standard AM broadcast band and the 160-m amateur band. This frequency range represents two octaves, about as much as can be optimally matched with a single coupling solution.

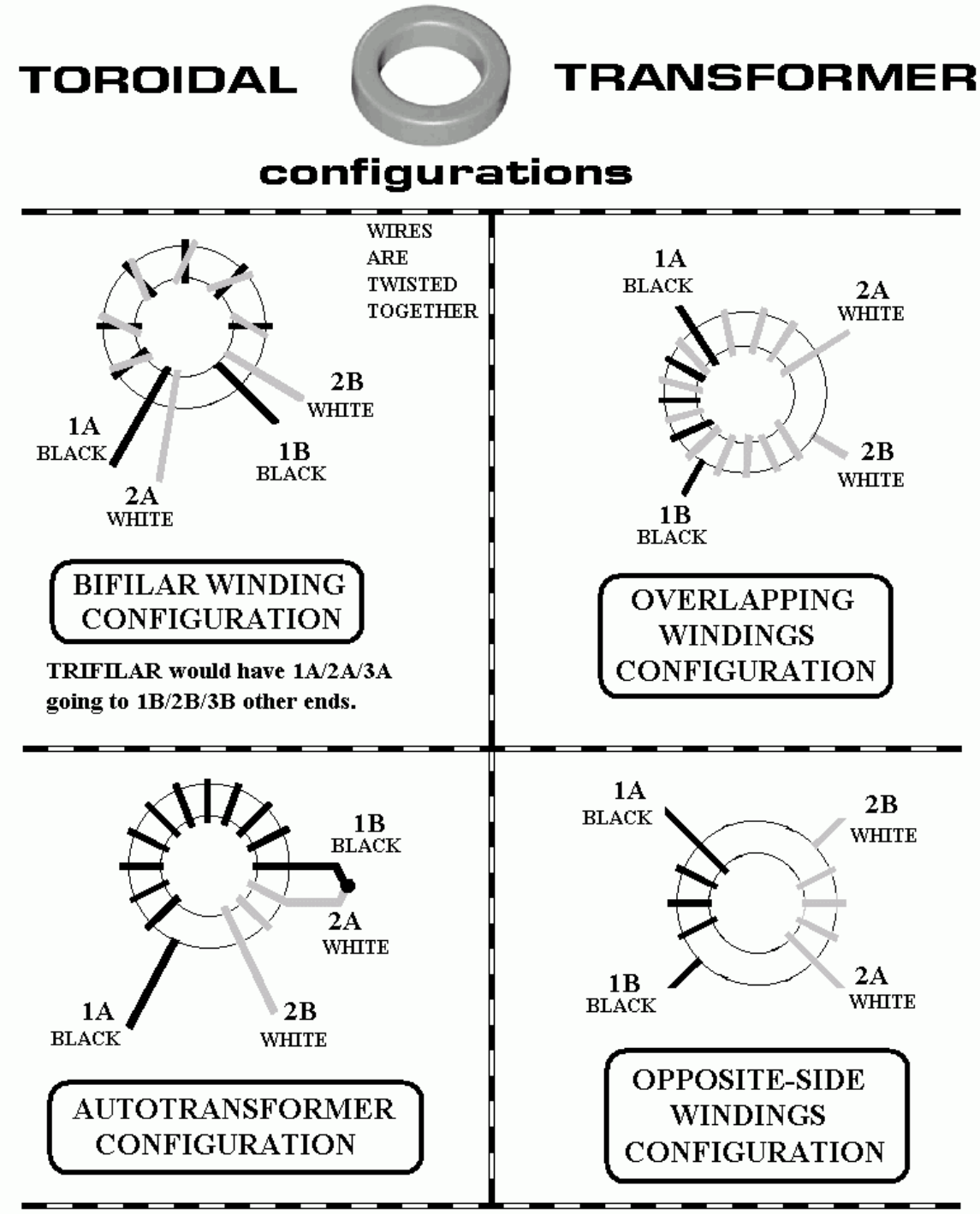
With all antennas, a narrowband L-C conjugate match transfers the most signal at a given frequency but, often, a broadband method is what's desired for the intended use. In many cases the amount of extra loss caused by "going broadband" is not that significant in the overall signal-to-noise picture. Broadband matching at medium frequencies is usually accomplished through the use of ferrite core transformers. These may use a variety of core material formulations and physical designs (toroidal, binocular, etc.).

Some inherently-broadband antennas have well-defined matching schemes. A Beverage antenna, for instance, should use a 9:1 transformer to couple its wideband 450-600 ohms down to 50-75 ohms compatible with receiver inputs. The same is true for the Ewe and K9AY designs. Flag, Pennant, and Kaz/Delta terminated loop antennas should be operated with a 16:1 transformer. Other antenna types have optimum associated matching transformers as well. I have determined a number of these through experimentation.

Ready to use transformers are sold by Mini-Circuits ("http://www.minicircuits.com/"). These include T1-6 (=1:1), T2-1T (=2:1), T4-6T (=4:1), T9-1 (=9:1), T16-6T (=16:1), TT25-1 (=25:1), and T36-1 (=36:1). Each of these has a suffix such as –X65 or –KK81 denoting lead style, e.g. T16-6T-X65 is a 6-pin DIL/DIP lead configuration of the T16-6T transformer. While these are small and remarkably wideband compared to most "homebrew" RF transformers, they cannot handle much power. Excessive RF can cause distortion products and, in the worst cases, permanent damage. These should not be used at amateur radio multi-operator contest sites where several transmitters may be active close to the receiving position. The windings of the Mini-Circuits transformers should not be used to pass direct current of more than a few milliamperes. For these reasons, there are still occasions where you need to "roll your own" transformers.

A "power user" of ferrite cores, John Devoldere, ON4UN, recommends the Ceramic Magnetics MN8CX toroids. These are sold by Misek Antenna Research ("http://exax.net/index.html"). Core materials 43, 61, 73, 75, 77, and J have all been used in this frequency range with reasonable success. Amidon ("http://www.amidon-inductive.com") and CWS-Bytemark ("http://www.cwsbytemark.com") stock these cores. 75 and J materials are pretty much the same thing. These give the best results in many of my tests of toroidal cores. Type 43 is often useful as well. Some of the common methods of winding toroids are shown in Figure 1 below.

Figure 1



John Bryant's excellent article "Fabricating Impedance Transformers for Receiving Antennas" ("http://home.comcast.net/~markwa1ion/exaol2/z_transformers.pdf") concentrates on opposite-side winding techniques and the usage of ferrite materials 43 and 75. These opposite-side winding transformers work reasonably well below 5 MHz. Tests I've done indicate that multifilar

windings cover a greater frequency range, but may be more likely (because of interwinding capacitance) to unbalance, or cause more feedline interaction with, "touchy" antennas such as the Flag and Pennant. Bill Bowers, in the LWCA "Lowdown", did a series of articles entitled "Ferrite Facts". His main area of interest is the 100 kHz to 500 kHz longwave range. Bill recommends broadband transformers that use a winding impedance (inductive reactance) equal to 5 or 6 times the intended ohmic load, rather than the "times 4" rule usually used. He made one statement that runs contrary to my test results: "Both types #75 and #J have so much loss above 500 kHz that they should not be considered for use in MW." I have bench test data showing that a 7 turn trifilar 9:1 transformer on an FT114-75/J core has a flatter response curve than a similar 11 turn trifilar transformer on an FT140-43 core right up to 30 MHz. Insertion loss with the 75/J transformer is within 1 dB of an ideal 9:1 transformer whereas the type 43 version has some points with loss in excess of 2 dB. These results are presented at the end of this article.

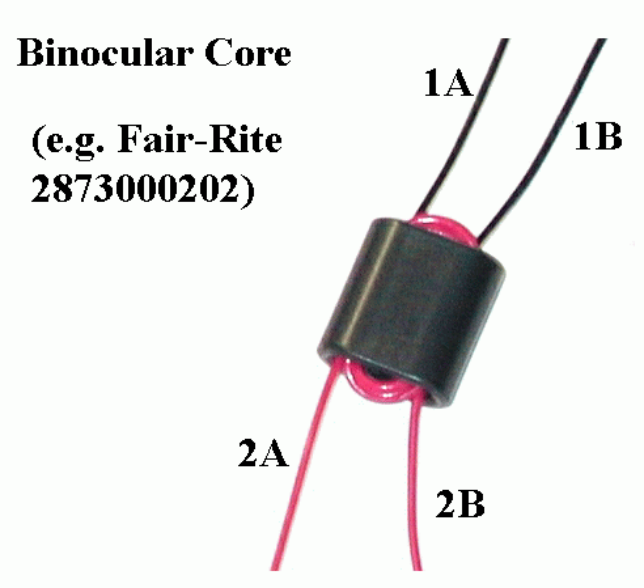
Multifilar windings produce ratios of 1:1, 4:1, 9:1, 16:1, etc. that, when ground is common, are the square of the number of wires in the (usually twisted) multifilar bundle. Separated-ground transformers have one additional winding in the bundle.

A 9:1 trifilar transformer has the high-impedance feed at lead 1A, leads 1B and 2A are joined, leads 2B and 3A are joined and connect to the low impedance feed, and lead 3B is common ground. For a 9:1 multifilar transformer requiring separate grounds (or a balanced load on either or both sides), a quadrifilar bundle is required: 1A is one side of the high impedance load, 1B and 2A are joined, 2B and 3A are joined, 3B is the other side of the high impedance load, 4A is one side of the low impedance load, and 4B is the other side of the low impedance load.

When you need a transformation ratio other than 1:1, 4:1, 9:1, etc., you can go in a tapped autotransformer configuration (OK if ground is common) or you can use the opposite-side or overlapped winding configurations as shown in Figure 1. The opposite-side windings configuration has the poorest high-frequency performance because of the decreasing magnetic coupling efficiency of ferrite as frequency increases. In some applications, roll-off above 5 MHz could be a good thing, a form of low-pass filtering that could make mixing / IMD products from powerful shortwave broadcasters less likely to show up on the medium-wave broadcast and 160-m amateur bands.

Tom Rauch, W8JI ("http://www.w8ji.com"), has done a good deal of matching transformer experimentation. He endorses binocular cores such as the Fair-Rite 2873000202, made of ferrite material #73. His web site has a link to an informative article "Balun and Core Selection". The binocular core (Figure 2) provides a tighter coupling between a primary and a secondary that are not in a multifilar winding. Random ratios can be achieved with less core loss than with opposite-side or overlapped windings on a toroid. An approximately 12:1 ratio transformer would consist of 10 turns high-impedance winding and 3 turns low-impedance winding: 3 turns low-Z* (12 ^ .5) = 10.39 turns high-Z.

Figure 2



Antennas such as Flags and Pennants should operate with a similar lack of feedline interaction as can be had with opposite-side windings on a toroid. The performance into the HF bands will be superior. A bench test run on a 16:1 binocular core transformer (12 turns / 3 turns) shows minimal loss compared to an ideal transformer over the 0.3 to 30 MHz frequency range.

Which Transformer for Which Antenna – several test cases

As noted above, some antennas have a fairly predictable impedance over a wide frequency range. I'll address these first, since their matching solutions are straightforward and well understood. Then some other less commonly used antennas will be discussed.

Beverage Antenna; K9AY and Ewe antennas

A homebrew 9:1 transformer such as an FT114-75 or J core with a 7 turn trifilar winding does well here when the same ground is used on both sides of the transformer. If the ground must be separated, go to a quadrifilar winding: antenna=1A, 1B=2A, 2B=3A, field GND=3B, coax. to 4A (center) and 4B (shield). A Fair-Rite 2873000202 binocular core with 9 turns high-Z and 3-turns low-Z will also do well. Opposite-winding transformers, as suggested by John Bryant, can also be used: an FT114-75 or J core with 21 turns opposite 7 turns would be my first choice there. With this, expect roll-off above 5 MHz. This might be desirable or undesirable depending on your intended usage. Avoid the Mini-Circuits T9-1: its coupling efficiency degrades below 1 MHz and it is prone to static damage.

Flag, Pennant, and Kaz/Delta Terminated Loop Antennas

Use a Mini-Circuits T16-6T transformer in small-signal areas or, for better results, wind a 16:1 transformer such as an FT114-75 or J core with a 28 turns opposite 7 turns. On an FT140-43

core, you'd use 44 turns opposite 11 turns. Extended frequency range operation may be obtained with a binocular core having 12 turns high-Z and 3 turns low-Z.

Tests of other antennas

In all cases a Mini-Circuits CAT-10 attenuator (10 dB) was inserted in the feedline at the output of the antenna transformer being tested. This reduced the effects of any odd loading if receiver input impedance was somewhat different from pure 50-ohms. Results given apply to signals received in the 380 to 2000 kHz frequency range.

Test Case 1: a 1.8 m (6 ft.) vertical whip
Preferred broadband match = 100:1 transformer

On the face of it, one would think that this is much too small an antenna to deliver any useful signal, without amplification, at frequencies much lower than 5 MHz. The usual approach is to use a high to low impedance buffer amplifier (such as a TI / Burr-Brown BUF634) to couple a short "E-field probe" such as this to a 50-ohm input receiver. And this is exactly what you should do … most of the time.

A drawback is that amplifiers can cause intermodulation distortion (IMD) products at strong signal locations. A strong signal on 6100 kHz and another strong signal on 7200 kHz can react in the amplifier to produce undesired second order distortion signals at the difference frequency of 1100 kHz and at the sum frequency of 13300 kHz. Third order products can occur at the lower frequency minus the spacing (6100-1100=5000) and at the higher frequency plus the spacing (7200+1100=8300). Urban areas cause the greatest amplifier stress. Dallas Lankford, in a project done for the AMRAD group, has designed a very high intercept point amplifier, but it requires a 28 volt DC supply and an expensive transistor.

Another problem is that, to maximize signal-to-noise ratio, such short whips are placed outdoors, often on a high mast or roof, exposed to the weather. The amplifier, co-located with the antenna, is more likely to fail in this setting than if indoors. If the whip could be efficiently and passively coupled to the 50-ohm feedline, a durable urban-capable antenna can be set up outside. With proper weatherproofing of the transformer box and feedline connection, a very low maintenance antenna can be had. Amplification, if still needed, can be applied indoors at the operating position. Most likely, in the city, you'd be using high-Q regenerative preamplification rather than something that's broadband. In less RF-intense areas, you could use a W7IUV or other 50-ohm in / out broadband amplifier at the receiving position.

Three matching transformers were tried. Best results were with a 100:1 autotransformer consisting of 70 turns total on an FT140-J core. This winding occupied about two-thirds of the core. One end of the 70-turn winding went to the whip and the other end to ground. The low impedance output was from a tap 7 turns from the ground end and 63 turns from the antenna end. Nearly as good results were obtained with a 64:1 transformer consisting of 64 turns opposite 8 turns on an FT114-J core. Readings across the 380 to 2000 kHz range were within 2 dB of those obtained with the 100:1 version. In third place was the Mini-Circuits T36-1-X65 transformer.

Its output level trailed the homebrew 64:1 and 100:1 models by about 3 dB around 1600 kHz and by at least 6 dB down below 800 kHz.

Test Case 2: a 2 m (6.6 ft.) per side square one-turn loop in vertical plane
Preferred broadband match = 1:1 transformer

This is an antenna which is valuable in field-site applications when a pattern other than that of an omnidirectional vertical is desired from an antenna that can fit on the roof of a (stationary) car. For home use, it can be mounted on a mast or on a roof. The feedpoint is usually at the center of the bottom side where the only break in the wire occurs. This balanced broadband loop has intrinsically less electrical noise pick-up than a whip or other antenna worked against common ground. It produces a figure-of-8 pattern. When phased against a vertical whip, a cardioid pattern can be produced. Two or more of these small loops can be spaced about 50 m apart to form a steerable-beam array with the right phasing scheme. Because this antenna is physically small for the frequency range that we're attempting to cover, amplification is often needed. As in the case of the whip, it would be preferable in terms of reliability to apply gain at the receiving position rather than at the location of antenna itself. This idea only works if the antenna can be coupled to 50-ohms with minimal loss. Several transformers were tried including Mini-Circuits 2:1 and 4:1 models set up in both step-up and step-down configurations. The Mini-Circuits T1-6-X65, a 1:1 model, gave the most efficient signal transfer in the 380 to 2000 kHz range. A homebrew 1:1 transformer, comprised of an FT114-J core with 7 turns bifilar wire, worked equally well; this would be preferred at high-signal locations over the Mini-Circuits version. One winding goes to the two antenna leads and the other winding goes to coaxial cable center and ground. A binocular core using two 3-turn wires would also work.

Test Case 3: a 4.4 m (14.5 ft.) per side square one-turn loop in vertical plane
Preferred broadband match = 4:1 transformer

This larger version of the Test Case 2 antenna is used outdoors at home installations for a low-noise antenna having more output level than the smaller broadband loop. Usually this is mounted as high in the air as can be accommodated. Two of these can be set up at a right angle and/or separated about 50 m for phasing use.

Of the several transformers tried, the 4:1 Mini-Circuits T4-6T-X65 did best. A homebrew equivalent would be a Fair-Rite 2873000202 binocular core with a 6-turn antenna winding and a 3-turn winding going to the coaxial feedline to the receiver. The best toroid implementation would be an Amidon FT114-J with a 7 turn trifilar winding: 1A=antenna lead A, 1B+2A joined, 2B=antenna lead B, 3A=coax. cable center, and 3B=coax. cable shield.

Test Case 4: a 30.5 m (100 ft.) end-fed horizontal longwire, about 1.5 m off ground
Preferred broadband match = 9:1 transformer

This is the "plain vanilla" antenna used by many DXers. It will work connected straight to a receiver's input, but quite a bit more signal can be squeezed out of it if it is matched correctly. In a narrowband sense, you'd use L-C tuning. For efficient broadband coupling, a 9:1 transformer does best. In this case we're talking about an FT114-J with a 7 turn trifilar winding, rather than

the mediocre Mini-Circuits T9-1. Lead 1A goes to the antenna, 1B and 2A are joined, 50-ohm output is at joined 2B and 3A leads, and common ground goes to 3B. If "station" and "field" grounds are to be separated for noise reduction, you'll need a quadrifilar winding with the fourth winding feeding the coaxial line. There would be no connection at the 2B/3A junction and lead 3B would go to the field-site ground rod system. Opposite side windings (e.g. FT114-J: 21 turns / 7 turns or FT140-43: 33 turns / 11 turns) could also work, but sensitivity above 5 MHz may suffer. A binocular core approach would be a 9-turn antenna winding and a 3-turn winding to feed the coaxial cable.

Test Case 5: a 10 m (33 ft.) base-fed vertical
Preferred broadband match = 16:1, 25:1, or 36:1 transformer

This antenna doesn't take up much space on an urban or suburban lot, but it delivers a reasonable amount of signal if properly matched. If no tree is available, a non-conductive mast can be used for support. A common ground configuration can be used, or use ground rods near the base of the vertical for a "field-site ground" offering less electrical noise. With a common ground scheme, you can use a toroid that is wound autotransformer style, e.g. an FT114-J with 30 to 40 total turns and a low-impedance output tap 7 turns from the ground end. With either grounding method, Mini-Circuits models T16-6T, TT25-1, or T36-1 are usable in low-signal areas. For separated grounds you can also take the binocular core approach. Use 15 turns in the winding connected to the antenna and field-site ground, and 3 turns going to the coaxial feedline.

Test Case 6: a 10 m (33 ft.) center-fed (5 m each side of feedpoint) vertical dipole
Preferred broadband match = 36:1 transformer

The short (less than 1/16 wavelength) vertical dipole is a bit less efficient than a base-fed vertical of the same length worked against ground. Still it can do well and may be less susceptible to electrical noise. Use a Mini-Circuits T36-1 or an FT114-J toroid with 42 turns (antenna leads) opposite 7 turns (coaxial cable feed). Satisfactory receiving above 3 MHz will require different (lower) transformer ratios.

Test Case 7: a 109.7 m (360 ft.) overall length horizontal loop
Preferred broadband match = 16:1, 25:1, or 36:1 transformer

In the backyard I constructed a rectangular wire loop with two sides of length about 30.5 m (100 ft.) and the other two sides about 24.4 m (80 ft.). Average height of the antenna was about 2 m (6.6 ft.) off the ground. This horizontal wire loop was fed at a break halfway along one of the 30.5 m sides. I tried many transformers on this since I had no idea what the best broadband coupling solution was going to be. Good results were obtained with any transformer in the 16:1 to 36:1 range, with the nod perhaps going to the 36:1. Though quite a different antenna from the previously-described 10 m base-fed vertical, the best broadband transformer method of feeding it will be the similar: Mini-Circuits models T16-6T, TT25-1, or T36-1 are usable in low-signal areas or use a binocular core approach with 15 turns in the winding connected to the antenna and 3 turns going to the coaxial feedline. You can also use an FT114-J toroid with 28 to 42 turns (antenna leads) opposite 7 turns (coaxial cable feed). This antenna has good output; it is balanced and can help the ratio of desired signals to local electrical noise.

Table 1

Antenna Sensitivity Comparison with best transformer (as described in article)
Five of the strongest daytime signals at Billerica, MA (71.221 W, 42.533 N) are used.
*Results are in **dBm** and are derived from calibrated S-meter reading + 10 dB added*
to compensate for the CAT-10 pad at output of antenna matching transformer

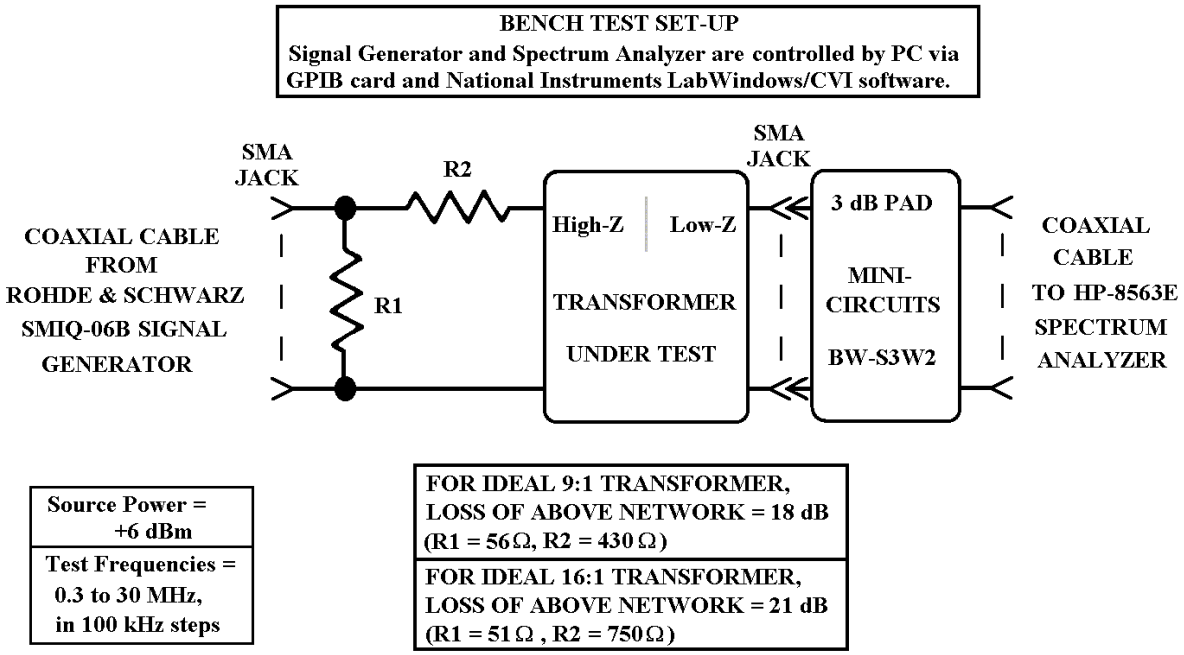
Station -->	WEZE	WRKO	WEEI	WBZ	WWZN
Frequency, kHz -->	590	680	850	1030	1510
Distance, km -->	17.5	4.4	28.3	39.7	16.1
Bearing, deg -->	141.5	177.9	187.9	134.6	174.2
Power, kW -->	5	50	50	50	50
(antennas are below)					
1.8m whip, 100:1 xfmr	-61	-29	-52	-50	-52
2m/side square loop, 1:1 xfmr	-63	-34	-65 (note 1)	-55	-63 (note 1)
4.4m/side square loop, 4:1 xfmr	-56	-22	-41	-50	-42
30.5m longwire, 9:1 xfmr	-39	-12	(note 1)	-26	(note 1)
10m base-fed vertical, 36:1 xfmr	-50	-10	-40	-40	-39
10m vertical dipole, 36:1 xfmr	-55	-15	-40	-41	-36
109.7m horizontal loop, 36:1 xfmr	-46	0	-28	-29	-26

note 1: Station is in or near a null of the antenna. Reading, if given,
cannot be used to judge the comparative sensitivity of this antenna.

Bench Tests of 9:1 and 16:1 Impedance Transformers

At work I have access to high performance professional RF automatic test equipment that I used at lunchtime on several occasions to test several transformers for insertion loss versus the theoretical loss. Figure 3 below shows the test set-up used.

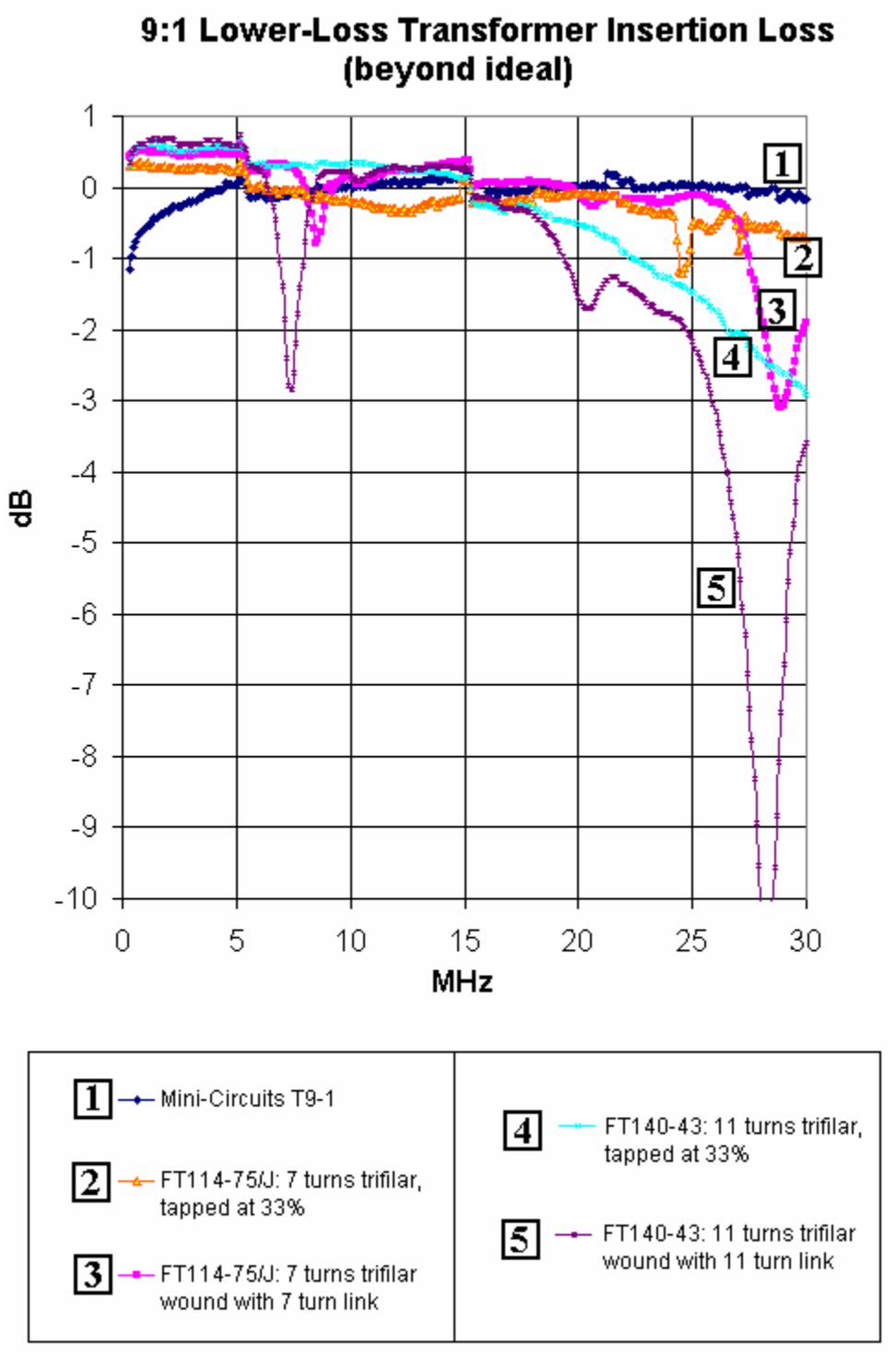
Figure 3



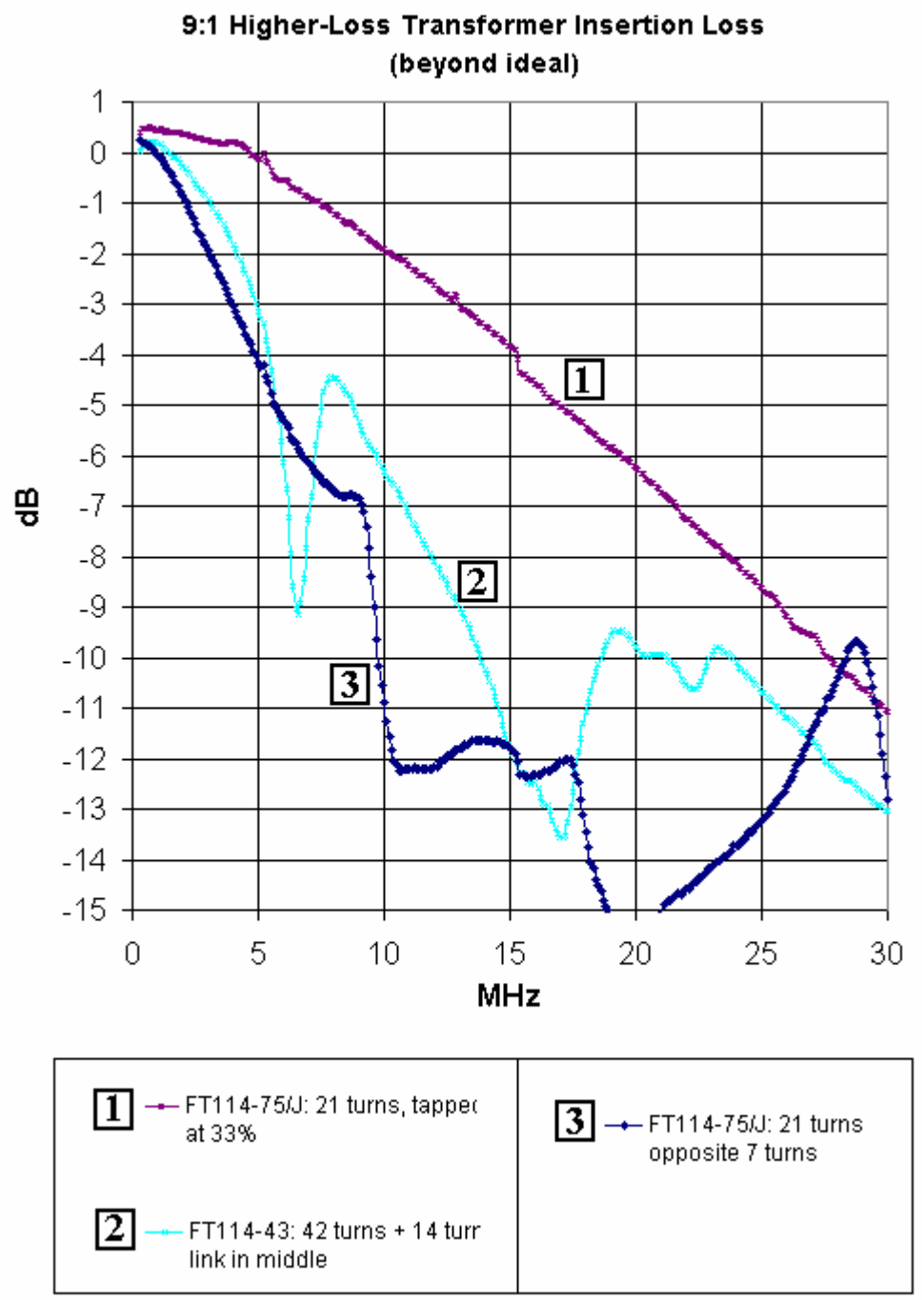
Transformers of each ratio tested are divided into “low loss” and “high loss” groups. All of the transformers tested had reasonable efficiency below 3 MHz. As frequency went up into the HF range, the Mini-Circuits, the binocular core, and the multifilar toroidal transformers showed superiority over the opposite-side windings types and several other configurations. Among the toroids, the 75 and J materials provided somewhat flatter response than the type 43. Type 77 showed “flaky” resonances that would be considered undesirable.

Test data were collected automatically by the PC in an Excel-compatible format. Graphs below show the loss beyond that which would be expected with an ideal transformer.

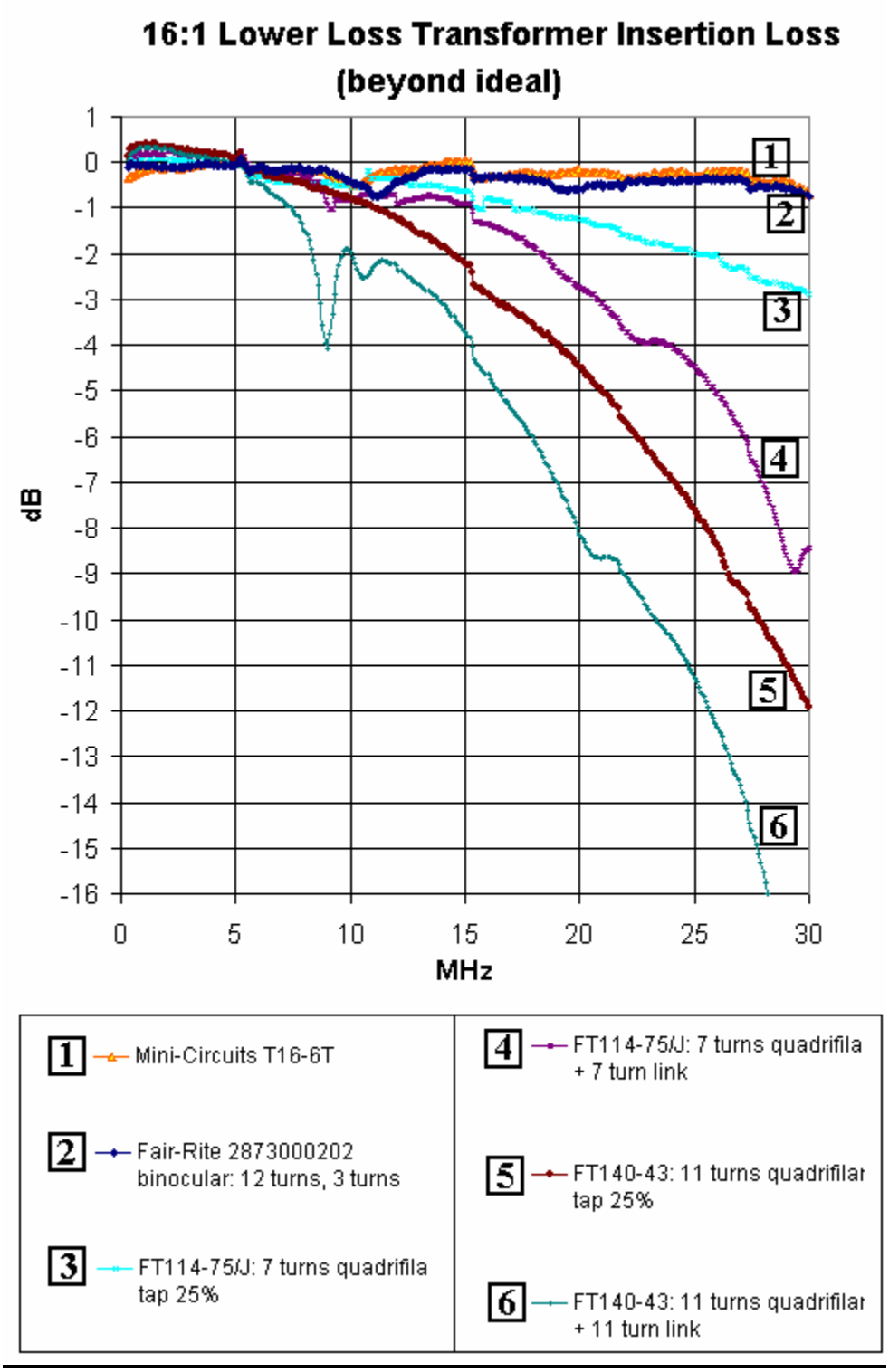
Graph 1 – Lower Loss 9:1 transformers



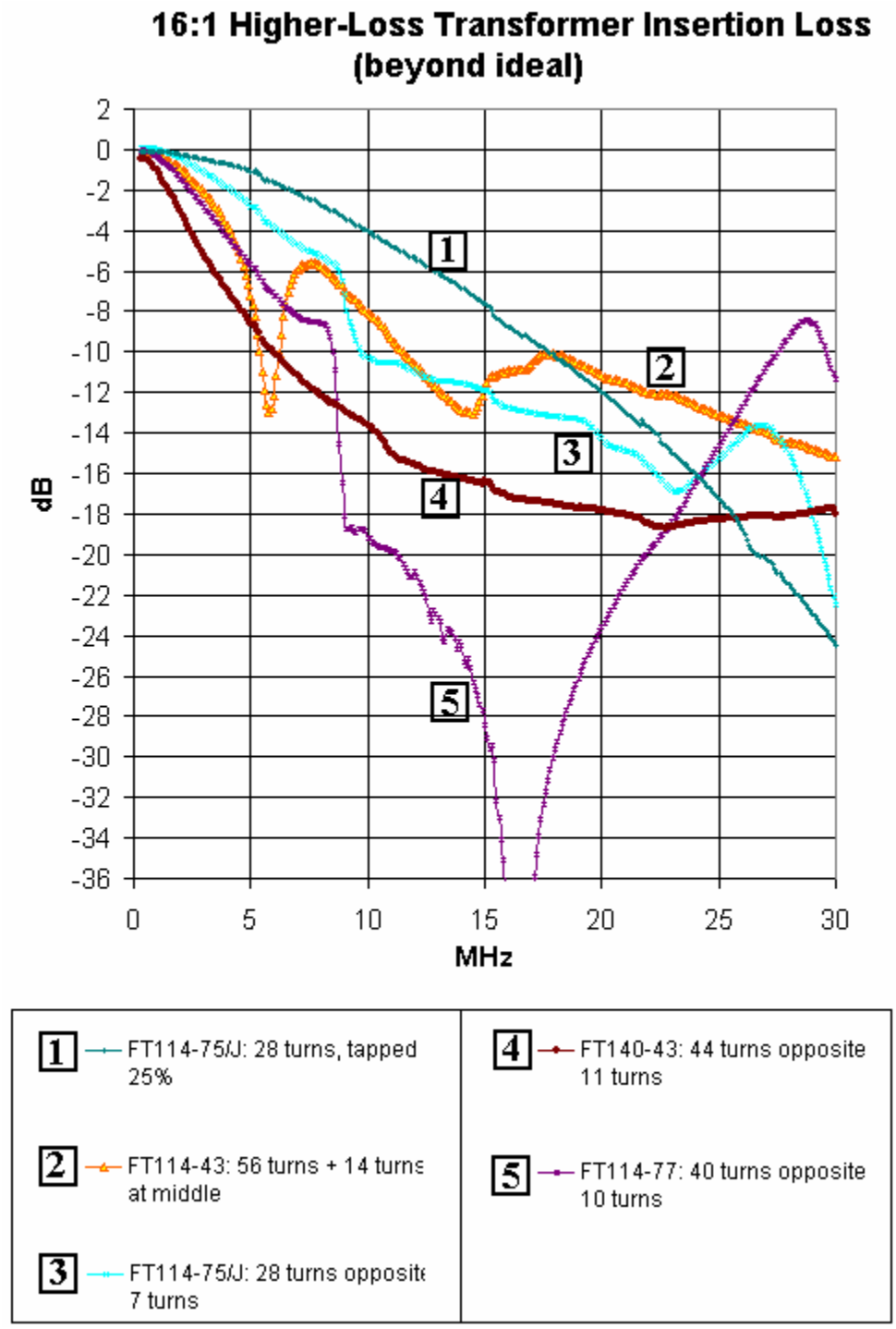
Graph 2 – Higher Loss 9:1 transformers



Graph 3 – Lower Loss 16:1 transformers



Graph 4 – Higher Loss 16:1 transformers



It is hoped that this article, like the works of others cited herein, stimulates further research and data collection for the benefit of radio hobbyists and professionals alike.