KIMBER KABLE
presents a reprint from Andrew Marshall's Audio Ideas Guide Winter 1995 of a technical discussion on loudspeaker cables.

Making The Connection, Part Deux:
A Closer Look At The Role Of Loudspeaker Cables.

by James H. Hayward

Recently retired from Bell Canada Special Services Engineering and Operations Groups, Jim Hayward is a Ryerson Electronics Technology graduate whose professional specialty has been data communictaions and radio systems. He is also a pianist and longtime audiophile, and currently teaches at Radio College of Canada in Toronto.

What's Good For The Interconnect Is Not Necessarily Good For The Speaker Cable.

As we covered much of the basic cable ground work in our previous article on interconnects, this one should be a snap, right? Well... yes and no. There certainly are many similarities between the interconnect and the speaker cable. In fact, they both form the vital link in a bridged voltage source application and we use the same equivalent circuit to model them. Also, the laws of physics, of course, are the same regardless of which end of the power amp you observe. That said, there is one environmental parameter that causes a profound difference in performance. It is the interface impedance. Its magnitude dictates which of the cable's electrical parameters dominate the behaviour of the interface. This, coupled with other considerations will impact on our selection criteria when shopping for effective speaker cables.

Okay, so you're willing to concede that a speaker cable is more than an interconnect cable with hormone problems that's traded its RCA plugs for spade lugs. What makes it so different? Which of its cable characteristics has the potential to affect your system's sound and which don't? Are there ways you can modify your system to minimize the negative effects? Let's find the answers to these questions and explore the reasons why. To do that, we will examine the role of the speaker cable, the impact that each cable characteristic has on your audio system's behaviour, how the power amp and speaker system influence the cable's performance as well as present measurements and observations of a number of speaker cable samples. To minimize reading obstacles, circuit equations and mathematical formulae are kept to a bare minimum. References are given for use by those who are interested in pursuing some of the topics in more scientific detail. Fortunately, there have been many excellent papers published that will help us in our quest for practical answers. *Figure 1* shows schematically an equivalent circuit of a typical power amp/cable/speaker interface. Referring to it from time to time will help in visualizing component interaction.

What A Speaker Cable Should Do

So what should a good speaker cable do? It must transport an analogue signal voltage from its source, the power amp output, to its load, a speaker system, without changing the signal's amplitude or shape. That sounds similar to the requirement for the interconnect cable, doesn't it...but there's a major difference. The interconnect cable transports a moderate signal level usually not exceeding one volt (rms values are shown unless stated otherwise) and is terminated in a constant, virtually resistive, high impedance load (greater than 10 kohms) that makes no demand for high current (usually not greater than 0.0001 Amp) from the source. Under these conditions, the series resistance and series inductance of the interconnect cable have negligible effect on the interface frequency and phase response as discussed in detail and shown by our risetime measurements.(ref.#1) The speaker cable, in contrast, must transport a high signal level that at times may exceed 40 volts and deliver it flawlessly to a low impedance load that may vary from less than 2 ohms to more than 20 ohms. Ohm's Law predicts with unfailing accuracy that under these conditions high signal current will flow through the cable and the speaker system. This high signal current is vital to retaining waveform integrity but is vulnerable to attenuation by the power amp's output impedance, Zs, cable resistance, R, cable inductance, L, and the contact resistance of poor connections. At this point, it may appear to some that I'm overplaying the importance of low cable impedance. After all, only very high current could contribute to significant power loss in the cable, right? Well, let's see how high the signal current can get. If your speaker system impedance never drops below 2 ohms, for example, your 200 watt power amp could be called upon to produce a peak current of 14 Amps. This is already high enough to be problematic but, believe it or not, it could even get substantially worse. To understand why, let's take a closer look at real world speakers and the magnitude of signal currents they must process.

How Current Hungry Are Your Speakers?

The impedances of individual speaker systems are rarely constant in magnitude or phase. A recent study (ref.#2) presented the Nyquist plots of the complex impedance curves of 21 speaker systems based on results from published reviews. It certainly wasn't good news for those who believe that the world would be a better place if all the audiophiles invested in transmission lines with a characteristic impedance of 8 ohms. The graph looked like a hound's breakfast, with the minimum impedance being one ohm and the maximum 28 ohms. Phase deviations abounded between maximums of +56 and -67.5 degrees. As if that wasn't bad enough, a number of scientific reports (ref.#3, #4, #5) indicate that certain dynamic signals (rectangular waveforms of a particular magnitude that can occur in recorded musical passages) applied to speaker systems can cause a current to flow that is up to two and one half times greater than that predicted by the speaker's minimum impedance! With possible dynamic loads below one ohm, cable manufacturers have a real challenge to keep speaker cable impedances as low as possible throughout the audio spectrum. But their efforts will be wasted if your power amp isn't up to the task of handling that heavy load as well. So let's now take a closer look at your power amp. Does it have what it takes to allow your system to benefit from low impedance cables?

Does Your Power Amp Have The Right Stuff?

So we need bags of current from time to time to make our favourite dynamic transients... well... dynamic. Where does all that current have to come from? That's right, Old Faithful, your power amp. If it's going to be up to the task, it needs to be blessed with some critical design features. First, a hefty power supply is essential. Without the energy reserve of a large power supply, high current waveforms fall under the heading of pipe dreams. Second, the power output stages must be capable of delivering and dissipating high power. If they can't, their ability to drive low impedance reactive loads will be impaired, with audible results. Output stages not up to handling the required high current may be designed to current limit when confronted with such daunting chores. In such cases, you will be treated to dynamic compression without your approval. Last, but certainly not least, your power amp's output impedance should be practically zero ohms throughout the audio spectrum. That's right, not one ohm or half an ohm but less than one tenth of an ohm. Why is this so important? A power amp must behave as much as possible like a perfect voltage source. In other words, its output voltage must not be influenced by changes in load impedance. Speaker system manufacturers are counting on it. Just because their speaker impedances vary all over the map doesn't mean that their products were designed with gay abandon. Those strange impedance irregularities reflect the electrodynamic behaviour of drivers and the complex crossover and compensation networks that are required to produce the most linear acoustic response possible. Yes, engineers could have included conjugate networks (more resistors, capacitors and inductors) so that their speaker system impedances are resistive as seen by the power amp; but increased cost, design complexity and possible sonic degradation due to additional components make this an unpopular option. Realistically, they cannot be concerned with trying to compensate for the shortcomings of individual power amps. They must assume that somehow you will get the signal voltage to the speaker system terminals with a flat frequency response. A perfect voltage source is the only device that has a chance of delivering its output signal voltage to its load, the speaker system, without losing some of it across its own internal impedance. Power amps with output impedances of even one ohm will exhibit a variable frequency response that mirrors the load impedance of the speaker system to which it is connected. Judicious use of low impedance output devices and negative feedback in a modern amplifier design will ensure that the output impedance remains acceptably low.

Why Is Interface Impedance So Important?

If the interface impedance determines the impact of cable characteristics, let's examine it more closely. First, impedance is the opposition to the flow of alternating current. Ohm's Law defines impedance, Z, as the ratio of a circuit's applied voltage, E, to the current, I, flowing in that circuit. The alternating signal voltage that appears at the output of our preamp or power amp contains the musical information we wish to reproduce. It causes an alternating current (one that moves in both directions) to flow through the cable and the load. The current waveform should contain all the amplitude, phase and frequency components necessary for the faithful reproduction of the signal voltage. If it does, it will recreate an identical copy of the signal voltage across the terminals of the load. This will happen if we have a perfect voltage source and perfect cables. Real world cables have resistance, R, inductance, L, and capacitance, C, that alter the current waveform.

Let's take an actual value of a cable parameter and see how its impact changes with the magnitude of the source and load impedance. 500 pF is a typical value for the parallel capacitance of a three metre length of either interconnect or speaker cable. As its capacitive reactance is lowest at high frequencies, let's analyze its impact at 20 kHz, where its nasty shunting to ground behaviour will be most detrimental. Its capacitive reactance is about 16 kohms at 20 kHz and this is in parallel with the load. If the source is a passive preamp with an output impedance of 16 kohms also, frequency response will be down 3dB at 20 kHz. Also, a high output impedance preamp must drive a very high input impedance power amp to avoid excessive loading. So if in our example, the input impedance of the power amp was 250 kohms, there would be over fifteen times more current flowing through the cable's capacitive reactance to ground than through the input of the power amp at 20 kHz! This frequency dependent loading results from the fact that the mathematical product of the output impedance of the preamp, Zs (if Zs is at least 10 times smaller than ZL) and the parallel cable capacitance, C, determines the time constant of a low pass filter. When the cutoff frequency of the filter invades the audio spectrum, as in the above example, errors in frequency and phase response and increased distortion result. Now let's perform the same cable capacitance reactance analysis on the speaker cable. All conditions are identical except this time the output impedance is that of a power amp and is a fraction of an ohm. The 16 kohm capacitive reactance is now in parallel with the speaker system load, which is never higher than 30 ohms. In this case, virtually all the signal current flows through the load as desired.

The Recipe For High Performance Cables

Fortunately, patterns emerge from the above exercise that make it unnecessary to go through it again for inductive reactance and resistance. To minimize sonic degradation, the simple truth is this:

1] A cable's shunt capacitive reactance, should be as high as possible.(C should be as small as possible) Like the load impedance, ZL, capacitive reactance must be at least 10 times and preferably more than 50 times greater than the value of the source impedance, Zs, at 20 kHz. Cable capacitance affects a high impedance interconnect interface more severely than a low impedance speaker interface. The interface bandwidth is determined by the following formula: $Bw=159{,}155/(Z_{th} \times C)$ where Bw is the bandwidth expressed in kHz, Z_{th} is equal to Zs x ZL/(Zs+ZL) expressed in kohms and C is the cable capacitance expressed in picoFarads. This warns that if Z_{th} or C or both are high, bandwidth will be limited.

2] A cable's series inductive reactance should be as small as possible.(L should be as small as possible) Like the source impedance, Zs, inductive reactance must be at least 10 times and preferably more than 50 times smaller than the value of the load impedance, ZL, at 20 kHz. Cable inductance affects a low impedance speaker interface more severely than a high impedance interconnect interface. The interface bandwidth is determined by the following formula: $Bw= (159{,}155 \times Z_{eq})/ L$ where Bw is the bandwidth expressed in kHz, Z_{eq} is equal to R + Zs + ZL expressed in kohms and L is the cable inductance expressed in microHenries. This warns that if L is high or ZL too low, bandwidth will be limited.

3] A cable's series resistance should also be as low as possible. Like the source impedance, Zs, resistance must be at least 10 times and preferably more than 50 times smaller than the load impedance, ZL, at all frequencies. Cable resistance dominates the cable's impedance from 20 Hz to 2 kHz and affects a speaker interface more severely than an interconnect interface.

Like many things in life, beyond some point of refinement, all parameters cannot be optimized simultaneously. As one of my warped friends likes to put it, "You can't have your Kate and Edith too."

We can, however, trade one parameter for another so that we optimize the cable design for a particular interface application!

The recipe for a superior interconnect cable is one that allows some increase in series inductance and resistance in order to obtain less shunt capacitance. Similarly, the recipe for a superior speaker cable is one that allows some increase in shunt capacitance in order to reduce series inductance and resistance.

How can we objectively prove that this is true? Review the risetime measurements and note the correlation with cable parameters.

What About The Magic?

Did I forget to mention the special weaves, or the critical dimensions, or the mix of size and position of the strands, or the special properties of certain conductors? No, it was intentional. Getting caught up in the details of the manufacturing processes and imaginative marketing explanations may be very interesting, but is really not very enlightening. The simple truth is that a cable's performance is reflected in the magnitudes of its basic electrical characteristics.

Don't misunderstand me; I do believe that the proper choice of materials and skilled craftsmanship can have a significant impact on a cable's performance. My point is, that if they do, it will show up in better L, R and C numbers. It is unnecessary for you to know how a cable was constructed or with what materials, but you should know its L, R and C values, and the impedance of the intended application. Armed with that data and the simple formula for bandwidth, you can accurately determine the performance of cable interfaces and predict potential limitations.

Beware Vast Claims Supported By Half-Vast Science

Sometimes misinformation creeps into the world of high end audio in the guise of scientific fact. There are numerous examples of valid physical and electrical behaviour being taken out of a technically correct context and applied inappropriately to audio. Perhaps the worst cases revolve around the misunderstanding that sound and electrical audio signals do not have the same wavelengths or travel at the same velocity. First, let's compare the velocity. At room temperature, sound travels through air at 343 m/s. In a typical cable, an audio signal will travel at half the speed of light or 150,000,000 m/s. Since wavelength=velocity/frequency, then the wavelengths at 20 kHz are 1.72 cm in air and 7.5 km in the cable. At 20 Hz, this same relationship is 17.2 m in air and 7,500 km in the cable. When cable lengths approach 1/30 of a wavelength we might want to consider transmission line effects. Does anyone plan to use cables in their system that are more than 250 m long? I didn't think so. There is absolutely no need to concern oneself with characteristic impedance, source and load matching, and signal reflections. To emphasize the point, let's look at an example.

I've heard from a reliable source that a speaker cable has actually been manufactured with a characteristic impedance of 8 ohms. Could this be the perfect gift for someone who has a speaker system that actually has an 8 ohm impedance from 20 Hz to 20 kHz? Hardly. First, such a speaker doesn't exist. So if the speaker's impedance and the power amp's output impedance are not 8 ohms throughout the audio spectrum, according to transmission line theory, then a mismatch exists and reflections result. This, of course, is nonsense unless we were actually going to use a cable that is at least 250m long. Imagine the power losses in the power amp and the cable. To make matters downright silly, to make a cable with such a low characteristic impedance, the manufacturer must actually make the dielectric more lossy. Leakage resistance (dielectric resistance) between the two conductors of a cable is the reciprocal of the fourth cable characteristic. It is usually referred to as cable conductance as is designated by the letter G. Normally, conductance, G, is, by good design, so low to minimize losses, that it can be ignored. Making G higher to modify the characteristic impedance creates a serious problem where there wasn't one and is....how can I say this politely...foolish!

In our last article, we proved that skin effect was, at best, a minor player. It seems that some people still have an unfounded fear of that bogeyman. There is no effect below 20 kHz for individually insulated wires that are 18 AWG or smaller. The impact of skin effect on larger diameter conductors is minuscule compared to the effects of its inductive reactance. Let the radio operators worry about it.

Frequency dispersion is another unnecessary concern that seems to plague some audiophiles. The effect results from the fact that the velocity of propagation through a cable is not constant at all audio frequencies. Long ago, the treble before bass effects were quite noticeable in long runs of unequalized telephone cables. Telephone companies solved the problem in the early years of this century by placing loading coils in series with the cable every so many miles to artificially increase its inductance, L. It was known, even in those times, that if the cable characteristics were such that L x G = R x C, then attenuation and velocity of propagation were independent of frequency. So should we increase the inductance or conductance of our interconnects to make the velocity of propagation uniform? No, because the cure is worse than the problem. Group delay for cables is typically 50 nanoseconds per metre (0.5 microsecond for a 10 metre length) and completely inaudible. Increasing cable inductance contributes to poor high frequency response while increasing cable conductance contributes to loss across the entire audio spectrum.

What about capacitor dielectric absorption (DA) effects? Could the cable dielectric contribute to audible distortion? There have been some fascinating articles (ref.#6, #7) prepared on DA as far back as 1955. The effect is that a dielectric of a capacitor tends to resist charging and discharging completely. It retains some of its charge and then, independently of exterior circuit elements, discharges to produce a DA recovery voltage. Although the effects are truly measurable in relatively large discrete capacitors, it is doubtful that such effects are large enough to impact upon the sonic integrity of a signal travelling through a reasonably short length of cable. Why? The magnitude of the DA recovery voltage is proportional to the average voltage and duration of the charging waveform. Even though musical waveforms are asymmetrical, they are still alternating voltages with an average value of zero and a duration, at most, of a few milliseconds. Also, cable manufacturers tend to use dielectric materials such as air or Teflon that display excellent DA characteristics. Remember, too, that a typical home cable's capacitance is about 2,000 times smaller than the discrete capacitors in which DA has been observed. Although many have tried, including yours truly, to measure DA in short lengths of cable, none to my knowledge have succeeded.

The Cable Samples

There were nine samples in all that ranged in length from approximately 2.3 m to 3.1 m. Seven of the group were legitimate speaker cables. One was a piece of coaxial cable, suggested by a friend because of its low inductance, that I borrowed from my ham shack and the last sample was a piece of the ubiquitous lamp cord. Each are coded C1 through C9 to simplify the plotting of graphs.

C1 Prisma-Time Compensated: large (16mm x 5.5mm), wide spaced (11mm), multistrand, parallel conductors, clear covering, terminated with thick (2mm), gold plated, spade lugs.

C2 Nordost Flatline: very thin (16mm x 0.7mm), 8 parallel conductors, clear covering, terminated with gold plated plugs.

C3 Kimber Kable 8TC: 16 individually insulated (half blue, half black), multistrand wires in a loosely woven braid(7mm dia.), terminated with thick, compressible (2.7mm), rhodium spade lugs.

C4 Kimber Kable 4TC: identical to *8TC* above except it has half the number of wires.

C5 Cardas Quadlink 5C: large (13mm dia.), multistrand, multi-conductor, blue covering, terminated with thick(2mm), rhodium, spade lugs.

C6 van den Hul The Revolution: 2 large individual cables (8mm dia.) complex multistrand, multiwire construction, dark orange covering, terminated with gold plated plugs.

C7 van den Hul Hybrid: large (20mm x 6.5mm), wide spaced (14mm), multistrand, parallel conductors, dark gold coloured covering, terminated with thick (2mm), gold plated spade lugs.

C8 Amphenol RG8/U: large (10.3mm dia.), coaxial cable used for HF radio transmission, dielectric material is solid polyethylene, centre conductor is multistrand copper, outer conductor is braided copper, black covering, terminated with PL-259 radio connectors.

C9 lamp cord (16 AWG): multistrand copper, parallel conductors, white covering, unterminated.

Testing Techniques

As both conductors contribute to resistance and inductance it was essential that loop resistance and loop inductance measurements be made. These along with the capacitance measurement were accomplished using a digital LCR meter. The results were then normalized to a standard length of 1 metre by dividing the results by the measured sample length. *Figure 2* presents the results in numerical as well as bar graph form.

Cable impedance measurements were made at selected frequencies throughout the audio spectrum using a function generator, a power amp and a 50 MHz oscilloscope. This was accomplished by applying exactly 1.00 volt (2.83 volts p-p) across a 1.00 ohm load resistor at each test frequency. The resultant voltage drop across the cable then provided the impedance directly in ohms. For convenience, the results are plotted graphically in milliohms in *Figure 3*.

The risetime measurements were made by observing the time required for the leading edge of a 2 volt (p-p) 20 kHz square wave to go from 10% to 90% of its full amplitude using a function generator, a power amp and a 50 MHz oscilloscope. These were done at both the power amp and the speaker ends of the cable. The actual risetime of the cable was then calculated using the Pythagorean difference of squares relationship. As the results are easily influenced by Zs and ZL, it is important to use a power amp with very wide bandwidth and a very low output impedance. I used a *Spectral DMA-50* power amp, borrowed from a friend, whose power bandwidth is 2 MHz and whose Zs measured less than 0.04 ohms at 20 kHz. I used a very large 4 ohm resistor as my ZL for all risetime tests. Risetime results are posted in the right hand column of *Figure 2*.

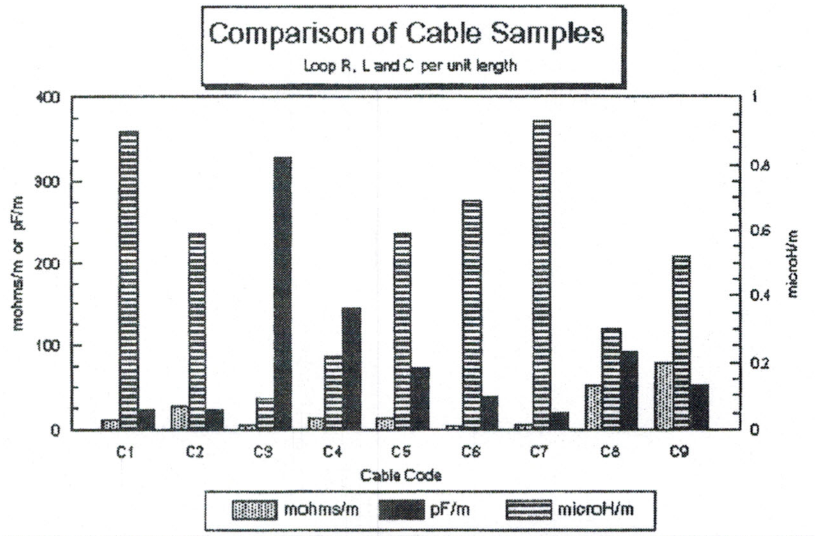
Risetime Tells The Tale.

The cable with the shortest risetime is the one with the largest bandwidth and is therefore the most desirable (Bandwidth=0.35/ risetime). Risetime is an excellent indicator of uniform frequency and phase response within the audio spectrum. In our previous article on interconnect cables, note the correlation between risetime and cable capacitance. Clearly the lowest capacitance cables have the shortest risetime and should be your first choice to work in a high impedance interconnect interface. Our speaker cable measurements here show a strong correlation between risetime and cable inductance. Clearly the lowest inductance cables have the shortest risetime and should be your first choice to work in a low impedance power amp/speaker interface. Note, too, that the cables with the best risetime also have the flattest cable impedance versus frequency results. This ensures that they also have the flattest, and therefore, the best frequency response. An interesting observation is that cables with very low resistance are only performance contenders if they also have low inductance. Above 2 kHz, inductance dominates the performance picture for speaker cables.

As one might expect, all cables, with the exception of the lamp cord, performed well at low and lower midrange frequencies because the undesirable effects of shunt capacitance and series inductance are minimal as they vary directly with frequency.

Figure 2

	Code	length(m)	mohms/m	microH/m	pF/m	Risetime(ns)
Prisma-Time Compensated	C1	3.097	11.6	0.90	22.6	317
Nordost Flatline	C2	3.060	26.5	0.59	23.3	207
Kimber 8 TC	C3	3.217	6.8	0.09	329.5	65
Kimber 4 TC	C4	3.252	14.5	0.22	144.5	98
Cardas Quadlink 5C	C5	3.051	13.4	0.59	73.7	193
van den Hul "Revolution"	C6	2.465	4.9	0.69	38.3	170
van den Hul "Hybrid"	C7	2.470	6.5	0.93	19.1	274
Amphenol RG8-U	C8	2.345	52.9	0.30	92.1	178
Lamp Cord (AWG 16)	C9	2.683	79.4	0.52	53.1	228



Cable Caveats

Keep your speaker cables short! Power loss in a cable is equal to the product of its resistance, R, and the square of the current running through it. Therefore, dynamic range suffers accordingly. If running longer interconnect cables is an option, do it. Just remember to avoid high output impedance preamps when considering that approach. Another way to minimize speaker cable power loss is to use more cables. That's right, bi-wire or bi-amp your system. Not only does this reduce the current in each cable but it provides significant sonic benefits by reducing intermodulation distortion as well. Bi-amping is expensive but, in my experience, the improvement is stunning.

Of course, there's the issue of good connectors and good connections. With high signal current being the dominant reality in the power amp/speaker interface, keeping contact resistance to a minimum is critically important. Basically there are two types of connectors in common use, the spade lug and the banana-style plug. Both have their advantages and disadvantages. The spade lug connection is usually superior electrically because it is compressed between the threaded nut and the base of 5-way binding posts. Sometimes, the thickness of the lugs or the limited space on the binding posts creates problems when attempting to place more than one set of cables on a given set of binding posts as in a bi-wiring application. Plugs, on the other hand, offer convenience and ease of use but do not always fit tightly enough to provide good electrical contact. There are, however, some outstanding binding posts that provide a special sleeve that will tighten around the plug to ensure excellent electrical contact. The best one I've come across is the *WBT-0700*. I purchased two sets of these a number of years ago and have found their superior design features a necessity in my lab. Gold plated connectors can work well provided that they are not damaged by the binding posts when tightened. Many of the binding posts installed in power amps and speakers are not equipped with a stationary, conducting saddle to prevent the shearing force from damaging the surface of the spade lug during tightening. Once again, look at the *WBT-0700* to see how good a 5-way binding post can be. Gold is soft and very susceptible to damage by abrasion so a practical alternative metal for spade lugs is rhodium. Its hardness will help ensure a long life in a rough environment.

And The Winner Is...

Using the selection criteria that we developed earlier and reviewing our measurement data, predicting the best performing cables is straight forward. Which ones had the lowest inductance, L, the flattest impedance versus frequency response and the shortest risetime? It was no contest for the Kimber cables. The *Kimber 8TC* took first place handily while the *Kimber 4TC* was an uncontested second. My piece of RG8/U coaxial transmission line finished in a not too shabby third place but it probably still is best left in the radio room.

Acknowledgements

Sometimes one is lucky enough to have friends that make life's little chores easier. I would like to thank my old friend, Roman Slocki, who has two of everything, for the use of one of his power amps. I also wish to thank a new friend and co-worker, Chris Rodgers of Radio College of Canada, for his generous assistance in the preparation of figures 1, 2, and 3.

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AIG, 175 Sherwood Avenue, Toronto,
Ontario Canada M4P 2A9
or call (416) 483-7573.

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2752 South 1900 West, Ogden, Utah, USA
(801) 621-5530 • fax (801) 627-6890

Figure 3

Frequency (Hz)	Code	20	200	1K	2K	4K	8K	10K	12K	14K	18K	20K
Prisma Time Compensated	Cl	25	20	30	45	110	280	370	450	540	710	780
Nordost Flatline	C2	45	40	40	50	110	220	280	340	390	510	570
Kimber 8 TC	C3	20	20	20	25	35	60	75	85	95	120	130
Kimber 4 TC	C4	25	25	25	30	55	110	130	155	180	220	240
Cardas Quadlink 5C	C5	30	30	30	40	80	175	225	280	350	460	500
van den Hul "the Revolution"	C6	15	15	15	25	55	135	175	220	265	350	390
van den Hul "Hybrid"	C7	15	15	15	30	85	235	310	390	460	600	660
Amphenol RG8MU	C8	35	35	35	50	90	160	195	220	250	300	330
Lamp Cord (AWG 16)	C9	110	110	60	110	185	360	440	500	550	660	700

Cable Impedance vs. Frequency