DEALING WITH NOISE AND INTERFERENCE IN ELECTRONIC INSTRUMENTATION CIRCUITS

SHIELDING, FILTERING AND USING LOW NOISE AMPLIFIERS

Many electronic instrumentation and data acquisition circuits must deal with low-level signals in the presence of strong interfering signals. If the signal level is small enough, even the noise produced by amplifiers and passive components can obscure the desired signal. In this article we will look at several strategies for solving problems with low signal level amplifier systems. These techniques include use of a low noise amplifier (LNA), filtering, circuit shielding, input leads shielding (including professional guard shielding techniques) and isolation of the circuit from the power mains.

By Joseph J. Carr

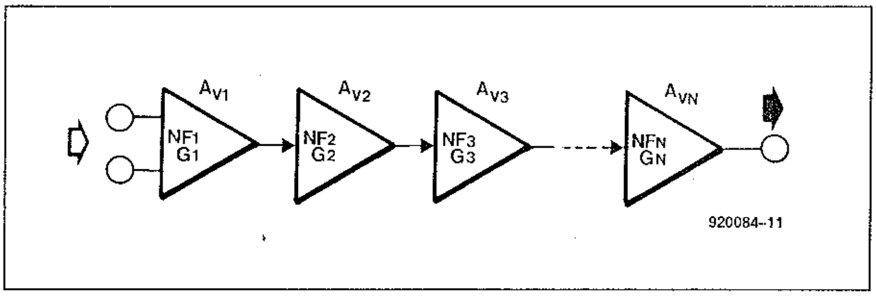

Fig. 1. **Cascade chain of voltage amplifiers.**

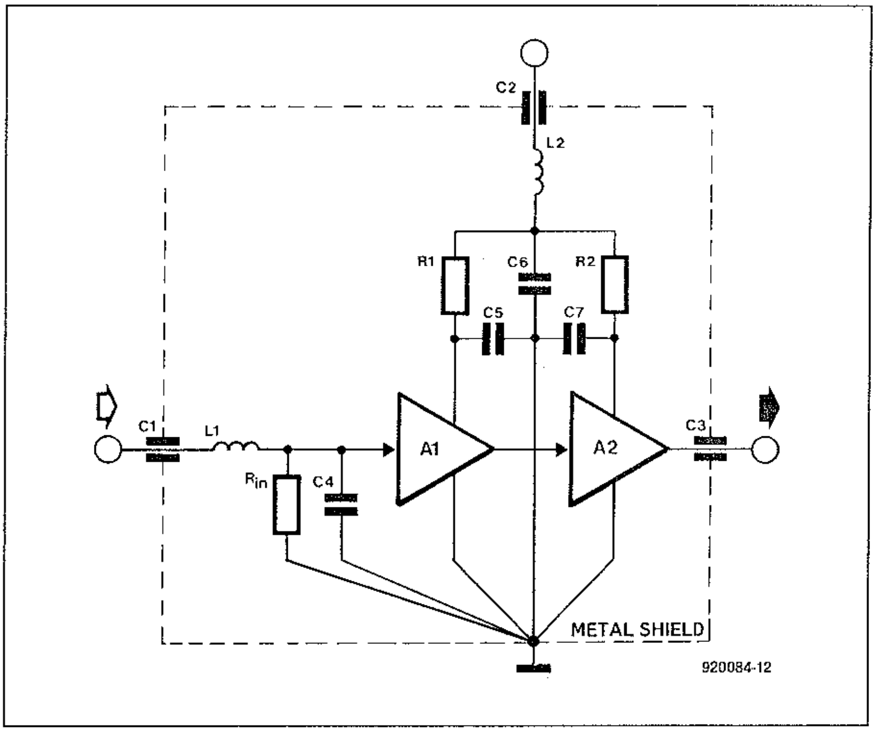

Fig. 2. **Generic electronic circuit showing use of shielding and filtering to eliminate noise interference.**

Noise, etc.

Noise can be defined as any unwanted signal, even though a somewhat narrower definition is sometimes sought in textbook treatments of the subject. But in the context of this article, *noise* can mean the internal 'hiss-like' noise generated in any amplifier, the atmospheric noise in radio receivers, 50 or 60 Hz hum picked up from the power mains, and interference from nearby sources of electromagnetic radiation (e.g., radio stations or other RF devices). Noise signals mix with, and either distorts or obscures the desired signals.

Several different forms of noise signal can be recognized: *white noise*, *impulse noise* and *interference noise*.

White noise supposedly contains all possible frequencies, so gets its name from analogy to white light, which contains all colours. Such noise is also called *gaussian noise*, although in reality it is neither 'white' nor 'gaussian' unless there are no bandwidth limits placed on the system. True white noise has a bandwidth from d.c. to daylight, and beyond. In practical electronic circuits, however, there are bandwidth limitations, so the noise is actually pseudo-gaussian 'pink' or even 'orange' noise. True gaussian noise can be eliminated absolutely by low-pass filtering, because it by nature integrates to zero, given sufficient time. Bandwidth-limited noise, however, does not integrate to zero, but to a low value. The effect of low-pass filtering on pink noise is therefore not total reduction.

An analogy to pseudo-gaussian or pink

noise is the 'hiss' heard between stations on an FM broadcast band receiver. Much of the noise in instrumentation systems is due to thermal sources, and has an RMS value of:

$$U_n = \sqrt{4KTBR} \quad (1)$$

Where:

U_n is the noise signal in volts (V);
K is Boltzmann's constant (1.38×10^{-23} joules per Kelvin);
T is the temperature in Kelvin (K);
B is the bandwidth in hertz (Hz);
R is the circuit resistance in ohms (Ω)

Noise can be generated in a passive component such as a resistor by virtue of its resistance. According to Eq. (1), in a circuit with a 1,000 Hz bandwidth and a resistance of 100 kΩ there is 0.6 microvolts (µV) of noise created by molecular motion due to temperature. Although this signal may appear to have a very low amplitude, keep in mind that many signals found in practical systems have the same order of magnitude. For example, in medical electronics, the electroencephalograph (EEG) machine records minute scalp potentials generated by the human brain's electrical activity, and may have components as low as 1 to 2 µV, with peak amplitudes in the 10 to 100 µV range. In that application, 0.6 µV represents a significant artifact, especially when amplified 5,000 to 10,000 times, as is common practice in EEG machines.

Part of the solution to this type of problem is to keep circuit impedances in the early stages — i.e., those stages that most of the gain follows — very low so that the resistance term in Eq. (1) is reduced to a minimum practical value. Additionally, low-pass filtering, bandpass filtering or other methods might be employed to keep the bandwidth term low.

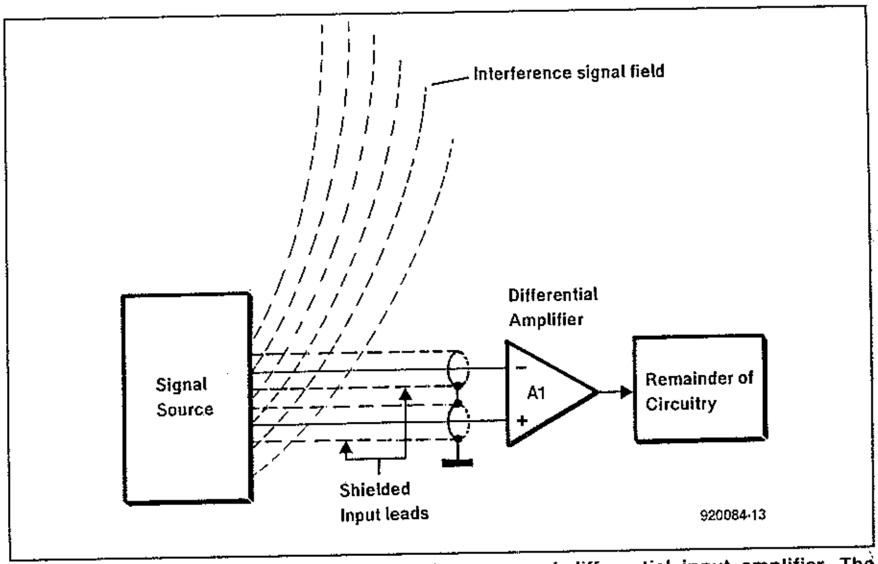

Fig. 3. **Generic instrument using a signal source and differential input amplifier. The shielding prevents external interference signal fields from invading the circuit — or does it?**

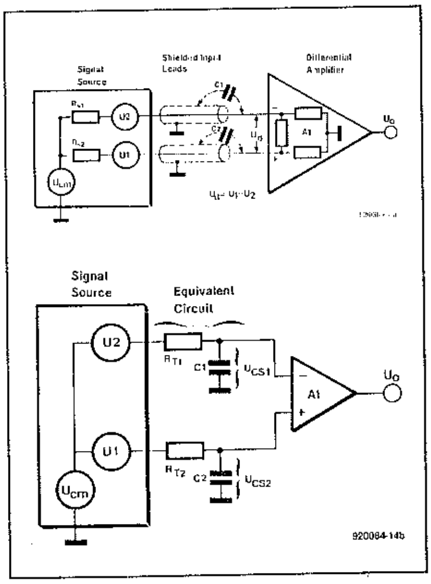

Fig. 4. **a) Typical circuit for a differential input amplifier circuit showing sources of resistance and capacitance in the circuit; b) equivalent circuit.**

There are several sources of noise that are peculiar to solid-state amplifiers: *shot noise*, *Johnson noise*, and *flicker noise*. In some amplifiers these noise sources can add up to a significant amplitude. Although low-pass filtering offers relief, it is better to specify a low-noise amplifier for the earliest stages in the system.

Friis' equation uses the noise factors (i.e. ratio of input to output signal-to-noise ratio) to show us that low noise amplifiers in the input stages provide most of the noise relief for the entire system. It is for this reason that satellite communications or TV earth stations use Low Noise Amplifiers (LNA) as preamplifiers on the dish antenna. Similarly, analogue instrumentation and data acquisition amplifiers use a single LNA in the front-end, and then ordinary amplifiers throughout the rest of the circuit. The Friis equation for a cascade chain of amplifiers such as Fig. 1 is:

$$NF_{total} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1} G_1 + \frac{NF_n - 1}{G_1 G_2 G_3 + G(N-1)} \quad (2)$$

Where:

NF_{total} is the noise factor of the entire cascade chain;
NF_1, NF_2, etc. are the noise factors of the individual stages;
G_1, G_2, etc. are the gains of the individual stages

Thus, we can use a single, usually premium low noise amplifier device for the first stage, and regular amplifiers for all others.

Low noise operational amplifiers are a good choice, but are sometimes rather expensive. A low cost alternative for many uses is the CA3130, CA3140 or CA3160 device in the 8-pin metal can package (not the mini-DIP!). Use a flexible heatsink of the type used for TO-5 metal transistor packages on the op-amp package, and operate the device from ±5 V dual polarity d.c. power supplies. This treatment (heatsinks and low power supply voltages) will mimic low-noise operation.

Other noise problems

Impulse noise is due to local electrical disturbances such as arcs, lightning bolts, electrical motors and so forth. Part of this same general type is general electromagnetic interference (EMI) problems. Such interference is usually caused by nearby radio transmitters, or other RF sources. It is not usually possible to force the transmitter off the air, even when it is an amateur operator, because they are licensed by the Government to be there ... while you are not.

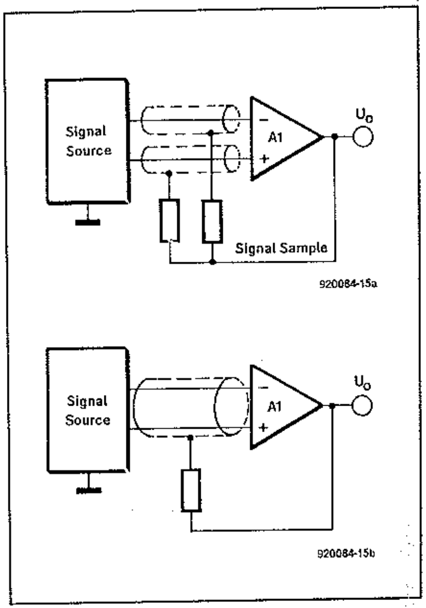

Fig. 5. **a) Simple guard shield drive circuit for twin shields; b) same circuit for single shield circuits.**

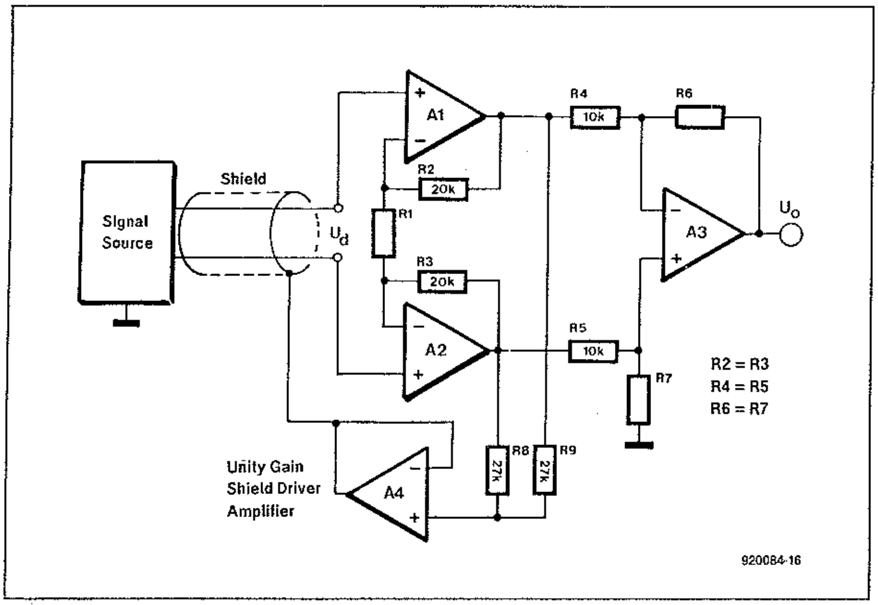

Fig. 6. Differential instrumentation amplifier, based on operational amplifiers, using an active guard shield driver (amplifier A4).

From an engineering point of view, your equipment might be very expensive and quite good, and still be very poor from an EMI point of view. The purpose of any electronic equipment is twofold: a) *it must respond to proper signals*, and b) *it must reject improper signals*. It is point 'b)' where most improperly designed equipment fails most significantly

Shielding and filtering of signal lines is the key to EMI problems. Figure 2 shows a generic circuit with several of the possible correction types used. First, note that the entire instrument is built inside of a shielded metal box, and the box is grounded. Points of entry and exit are passed through feedthrough 'EMI filter' capacitors. Feedthrough capacitors C_1 through C_3 have values of 50 pF to 2 nF (0 002 µF), depending on the circuit impedance and which capacitor is specified For example the signal line capacitors C_1 and C_3 will have smaller values, while power supply capacitor C_2 should be larger than 1 nF (0 001 µF).

Each stage in Fig 2 is isolated from other stages by a resistor, and has its own decoupling capacitor (C_5 and C_7). The main power bus is decoupled (C_6), and has a series radio frequency choke (L_2) to prevent RF that gets past C_2 from interfering with the operation of the circuit The input leads are similarly filtered with L_1 and C_4 The input resistance (R_{in}) of the amplifier and capacitor C_4 also form a low-pass filter with a frequency response that rolls off at a –3 dB/octave rate from the –3 dB point defined by:

$$F = \frac{1}{2\,\pi\,R_{in}\,C_4} \qquad (3)$$

Where:
F is the frequency in hertz (Hz)
C_4 is in farads (F)
R_{in} is in ohms (Ω)

Not all of the techniques of Fig. 2 are needed, or even appropriate, in all circuits Their inclusion was meant to show the possibilities, rather than form a recommendation for all applications. Select those that are appropriate or practical for your particular application.

Suppressing local interfering signals

Local interfering signals are created by other electrical devices close to the circuit being operated. and by the 50/60 Hz electrical power mains in the building Consider Fig 3. where a low-level signal source is connected to an amplifier at the input of a larger circuit. The signal source might be a sensor such as a Wheatstone bridge strain gauge an electro-optical detector. Alternatively, it may be a biopotential such as the EEG brain wave signal or electrocardiograph (EEG) heart signal The common factor shared by these signals is that they produce low level signals and often must operate in a high interference environment

A common solution to these problems is to use a *differential amplifier* at the input of the circuit. One of the properties of the differential amplifier is that its *common mode rejection ratio* (CMRR) tends to suppress interfering signals from the environment It does this job because the inverting (–) and non-inverting (+) inputs offer equal gain, but are of opposite polarity If identical signals are applied to the two inputs simultaneously, the net output voltage will be zero.

When a differential amplifier is used in a situation where it is connected to an external signal source through wires, those wires are subjected to strong local signals such as the 50/60 Hz a c. fields from nearby power line wiring. Fortunately, in the case of the differential amplifier the field affects both signal equally so the induced interfering signal is canceled out by the common mode rejection property of the amplifier.

Guard shielding

Unfortunately, the cancellation of interfering signals by the input amplifier CMRR is not total. There may be for example imbalances in the circuit that tend to deteriorate the CMRR of the amplifier These imbalances may be either internal or external to the amplifier circuit. Figure 4a shows a common sensor interface scenario, similar to Fig 3: a differential amplifier connected to shielded leads from the signal source, U_{in}. Shielded lead wires offer some protection from local fields but there is a problem with the standard wisdom regarding shields: *it is possible for shielded cables to manufacture a valid differential but erroneous signal voltage from a common mode signal!*

Figure 4b shows an equivalent circuit that demonstrates how a shielded cable pair can create a differential signal from a common mode signal The cable has capa-

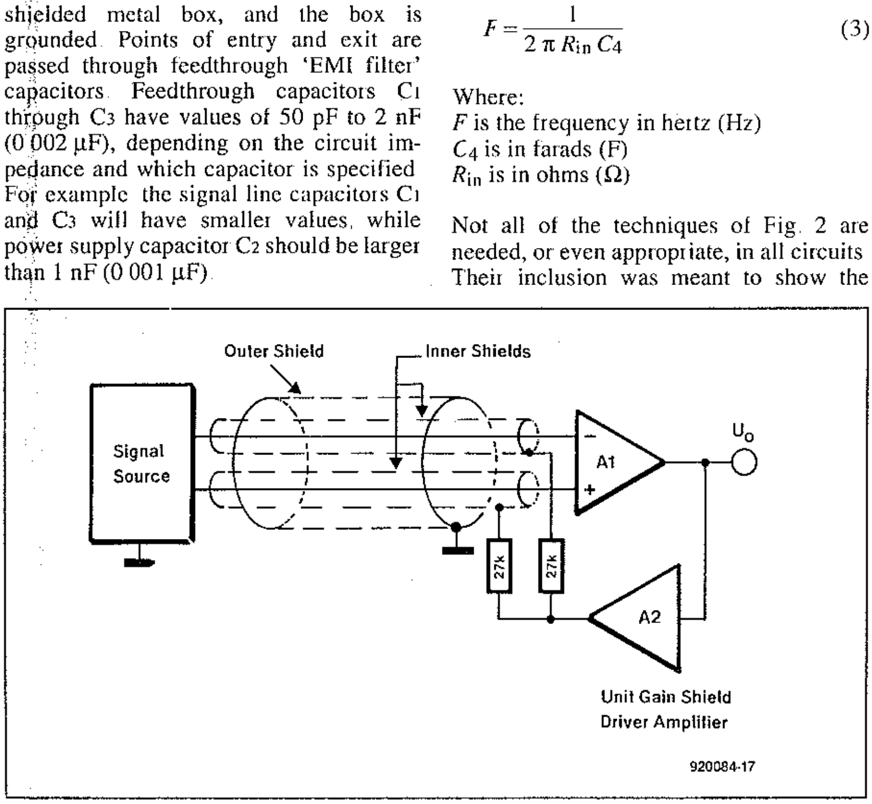

Fig. 7. Dual shielding combines twin-shield and single shield concepts.

citance between the centre conductor and the shield conductor surrounding it. In addition, input connectors and the amplifier equipment internal wiring also exhibits capacitance. These capacitances are lumped together in the model of Fig. 4b as C_1 and C_2.

There are also resistances in the circuit. The signal source resistances R_{S1} and R_{S2} are generally low, but in some cases (e.g., EEG, ECG, pH electrodes, optoelectronic sensors, etc.) they may be quite high. In addition, there are also input impedances, both differential and unbalanced to ground (see Fig. 4a).

As long as the sum circuit resistances are equal, and the two capacitances are equal, there is no problem with circuit balance. But inequalities in any of these factors (which are commonplace) creates an unbalanced circuit in which common mode signal U_{cm} can charge one capacitance more than the other. As a result, the difference between the capacitance voltages, U_{CS1} and U_{CS2} is seen as a valid differential signal by the amplifier.

A low-cost solution to the problem of shield-induced artifact signals is shown in Fig. 5a. In this circuit, a sample of the two input signals are fed back to the shield, which in this situation is not grounded. This type of shield is called a *guard shield* circuit. Either double shields (one on each input line) as shown in Fig. 5a or a common shield for the two inputs as in Fig. 5b, can be used.

An example of guard shielding for the standard three op-amp instrumentation amplifier, a very common differential front-end for electronic instrument circuits, is shown in Fig. 6. The instrumentation amplifier consists of A_1, A_2 and A_3, with associated resistors. If $R_2=R_3$, $R_4=R_5$ and $R_6=R_7$ the voltage gain of the circuit is given by:

$$A_v=\left(\frac{40\text{k}\Omega}{R1}+1\right)\left(\frac{R6}{10\text{k}\Omega}\right) \qquad (4)$$

(All resistance in kilo-ohms)

In Fig. 6, the gain can be set by selecting values for R_1 and R_6, which implies also a value for R_7 (which is equal to R_6). Variable gain control is provided by making R_1 variable. Keep R_1 away from zero ohms, however, or the gain will get very high very quickly.

In the circuit of Fig. 6, a single shield covers both input signal lines, but it is possible to use separate shields. In this circuit a sample of the two input signals is taken from the junction of resistors R_8 and R_9, and fed to the input of a unity gain buffer/driver 'guard amplifier' (A4). The output of A_4 is used to drive the guard shield.

Perhaps the most common approach to guard shielding is the arrangement shown in Fig. 7. Here we see two shields used: the input cabling is double-shielded insulated wire. The guard amplifier drives the inner shield, which serves as the guard shield for the system. The outer shield is grounded at the input end in the normal manner, and serves as an electromagnetic interference suppression shield.

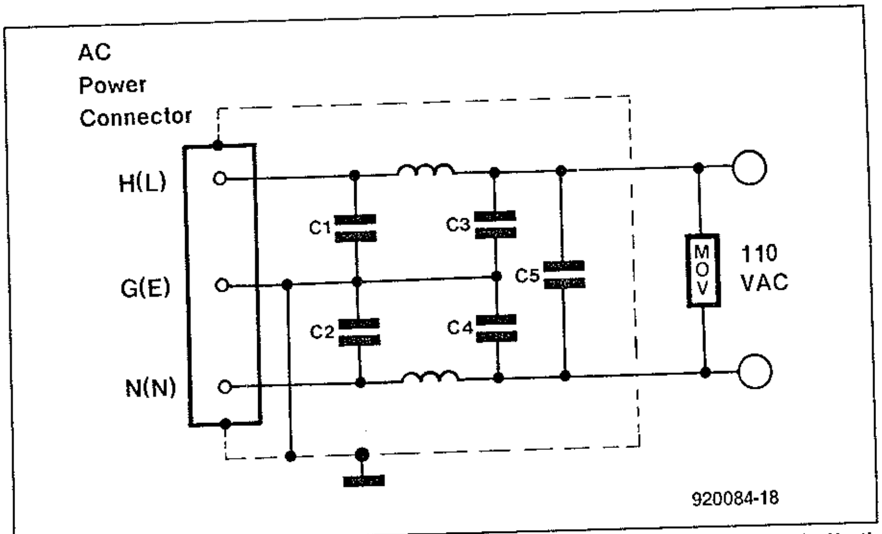

Fig. 8. **Shielded LC EMI filter for the a.c. power mains (wiring shown common in North America).**

Power line noise

Another potential source of interference is noise and EMI signals arriving on the a.c. power mains. I can recall digital instrumentation and computers in a medical school building that acted in a schizophrenic manner until it was identified that the a.c. power mains were the source of the problem.

A humorous event while this problem existed came about when the medical (M.D.) and medical sciences (Ph.D. and D.Sc.) students took the standard multiple choice national examination in human physiology. They used a 'mark-sense' answer sheet on which they use a pencil to darken the letter corresponding to the printed candidate answer they believe is correct. These papers were then taken to an optical scanner that input the answers to a computer. While the scanning was going on one year, some ac power line switching equipment started operating, sending high voltage transients over the mains. The result was that the entire freshman class of medical and sciences students flunked the national exam!

Where sensitive scientific instruments are used, one might want to consider designing the ac electrical power mains system to be either isolated from the building system, or having a separate system that keeps a separated neutral and ground conductor all the way back to the service entrance of the building.

Figures 8 and 9 show methods for dealing with severe power mains noise. In Fig. 8 we see an *L-C* power line filter wired in the North American standard manner. These filters are shielded low-pass filters, and are mounted inside of equipment as close as possible to the point where a.c. enters the cabinet. Some filters are available molded into the a.c. chassis connector. Exterior to the filter is a *Metal Oxide Varistor* (MOV) device used to suppress a.c. line transients above the normal peak a.c. voltage (some high voltage transients can reach 2000 V for 30 μs).

The transformer in Fig. 9 performs two functions. First, it isolates the equipment electrical system from the mains electrical system. Second, it frequency limits the system to prevent high frequency transients and pulses from passing into the equipment. It is my opinion, shared by many other engineers, that no computerized or other digital equipment — and many types of analogue equipment — should be operated in a noisy environment without one of these transformers. If the equipment is life-support, or life-saving, as it often is in medical applications, then it is probably engineering malpractice to design a piece of equipment without the transformer. ■

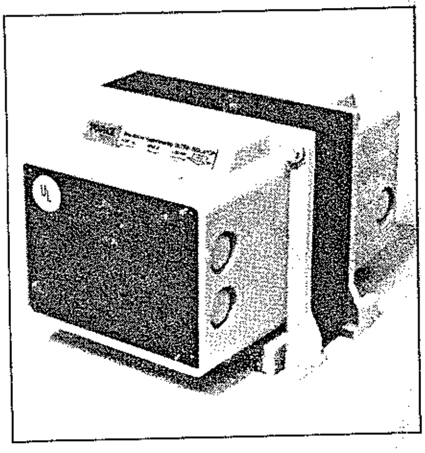

Fig. 9. **Line isolation transformer used with digital instruments, analogue instruments and computers to eliminate high voltage transients, mains voltage fluctuations and other problems. This transformer is manufactured by Topaz in the USA.**