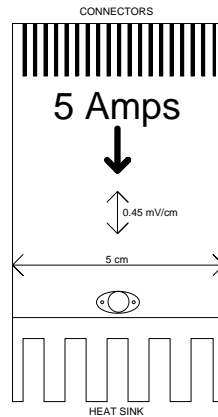


Measuring Ground Noise
by
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Fig 1.



Many engineers treat ground planes as if they were made of a superconductor rather than copper and assume that, no matter the current flowing in them, every part of a ground plane is at the same potential. While such an assumption may be reasonable on PC cards bearing only logic circuitry (or it may not, if the logic is very fast), it can lead to unacceptably low performance in PC cards carrying high precision or high frequency analog circuitry.

But if you can't measure it, it's not science. We can measure the resistivity of copper easily enough, it's $1.7 \times 10^{-6} \Omega \text{cm}$ at room temperature, and we can thence calculate or measure the resistance of the copper foil on a PCB. The standard "one ounce copper" has a thickness of 0.0015" (0.038 mm) and a sheet resistance of 0.45 m Ω /square. This is low, but is not so low that all ground voltages are necessarily insignificant.

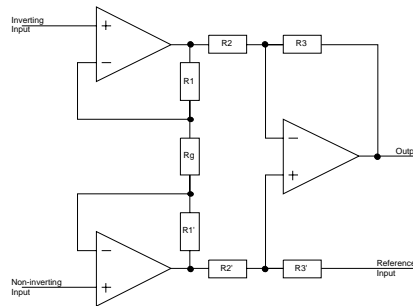
Consider a 5 cm wide board carrying a ground plane of one ounce copper with a connector at one end of the board and a power device, drawing 5 amps, at the other end with a heat sink (the heat sink, of course, is why the device cannot be near the connector).

The ground plane has a resistance of 0.09 m Ω per linear cm, so at 5 amperes the voltage drop in the ground plane is 450 $\mu\text{V/cm}$, quite enough to disrupt a precision (14-bit or more) ground-referenced signal.

This example, of course, is simple and easily calculated. In real life, and especially at high frequencies, where the inductance of a ground plane is not negligible either, it can be difficult to predict the voltage drop at different places on a ground plane, and thereby estimate its effect on circuit performance.

This note describes some simple techniques for measuring ground voltages as low as 1 μV .

Fig 2.

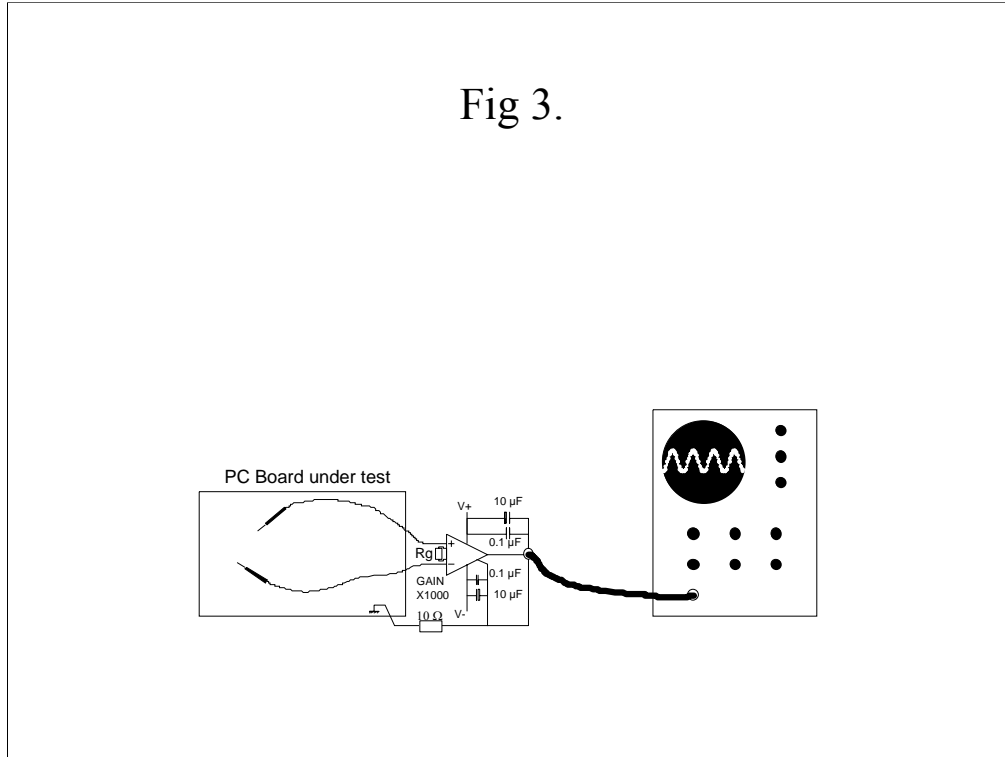


At DC and low frequencies (≤ 25 KHz) this is easily done with an instrumentation amplifier. An instrumentation amplifier (or in-amp) is an amplifier with a high impedance differential input, having high common-mode rejection, and a single-ended output. Unlike an operational amplifier it has an accurately defined gain (which may be adjusted by the user) and does not require feedback to its input terminals. It has an additional “reference” input which defines its output zero point.

There are several in-amp architectures, but the commonest is shown in Fig 2. The device consists of three op-amps and seven resistors. The precision of the device depends on the accuracy with which these resistors are matched, and the common-mode rejection in particular depends on R_1 and R_1' , R_2 and R_2' , and R_3 and R_3' being very well matched. For this reason it is better to use ready-made monolithic in-amps than to construct them from op-amps and discrete resistors.

Note that the reference input is applied to one of the resistors whose matching matters (R_3'). So the reference input must be driven from a source with a very low output impedance. If this is not the case the reference voltage must be buffered.

Fig 3.



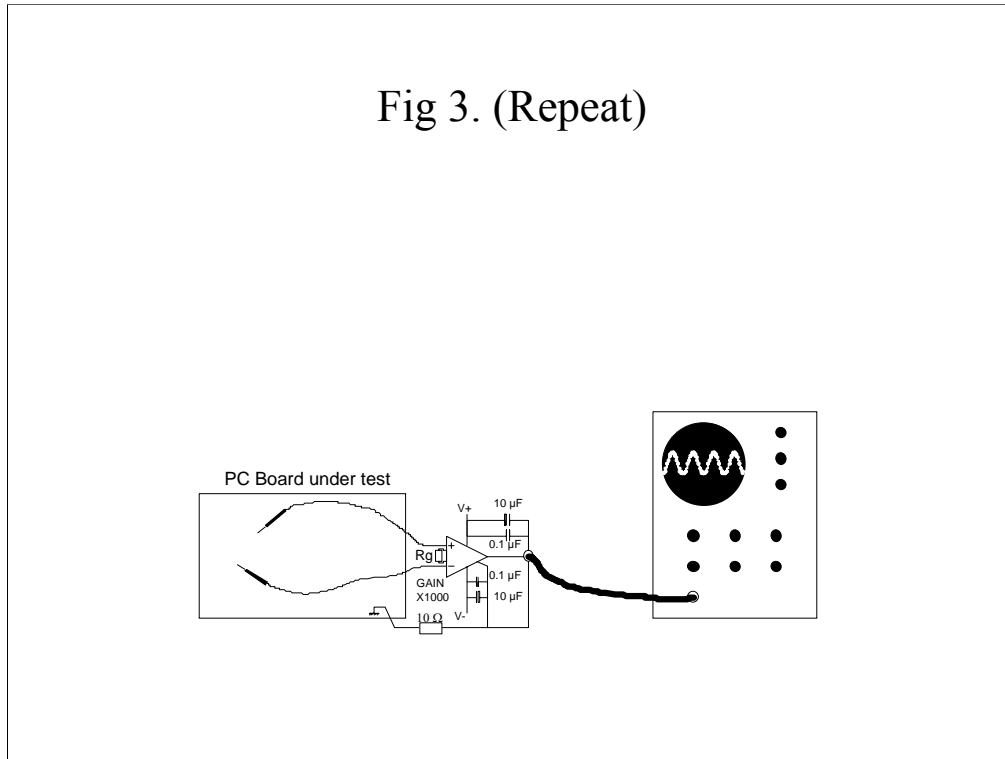
If we configure an in-amp to a gain of 1,000 and drive an oscilloscope from its output then the combination has a differential input sensitivity one thousand times better than that of the basic oscilloscope, and a high common-mode rejection (>100 dB at DC and LF). Most oscilloscopes have maximum sensitivity of 2 mV/div or 5 mV/div, which gives a working sensitivity of 2 μ V/div or 5 μ V/div.

The basic test set-up is shown in Fig 3. It is very simple – the output of an in-amp set to high gain is connected to the input of an oscilloscope and probes connected to the two inputs of the in-amp are used to measure very small potential differences on the ground plane of a printed-circuit board. But there are a number of issues which this diagram does not clarify but which must be considered. These include power for the in-amp, protection of the in-amp inputs, the input noise of the in-amp, ground noise between the oscilloscope and the board under test, bias currents, and pickup due to local magnetic fields.

Instrumentation amplifiers require power. In this application they require positive and negative supplies^[1]. The AD620 in-amp, which is very suitable for this type of measurement, will operate with supplies as small as ± 2.5 V or as large as ± 18 V. The negative and positive supplies need not even be of equal voltage as long as the total supply voltage lies between 5 V and 36 V. If the PC board under test has positive and negative supplies conforming to this undemanding requirement the power may be taken from the board under test – the AD620 draws at most only 1.6 mA (plus any current it may send to a load – in this application microamps at most), which is small enough to be acceptable to most systems. If the board under test cannot supply the necessary power (some boards may not have negative supplies, for example) it may easily be supplied by two small 9 V batteries in series, with the centre connection grounded to the in-amp reference terminal. In fact, the best arrangement to make this type of measurement consists of a small box containing the in-amp, its gain setting resistor and supply decoupling capacitors, and two 9 V batteries with an ON/OFF switch, a connector for a signal lead to the oscilloscope, and connectors for the two sense probes and a ground return lead.

^[1] Bipolar supplies are necessary because most in-amps have common-mode ranges which do not extend to their supplies. There are exceptions to this, but they are less suitable for this particular application.

Fig 3. (Repeat)



Some fifteen years ago Analog Devices manufactured such a test box and issued it to sales and applications engineers to lend to customers with DC and LF ground problems. Unfortunately it was so useful that none of our sales or applications engineers was ever able to recover one from a customer and after losing several hundred within a few months we stopped trying to keep up with our losses!

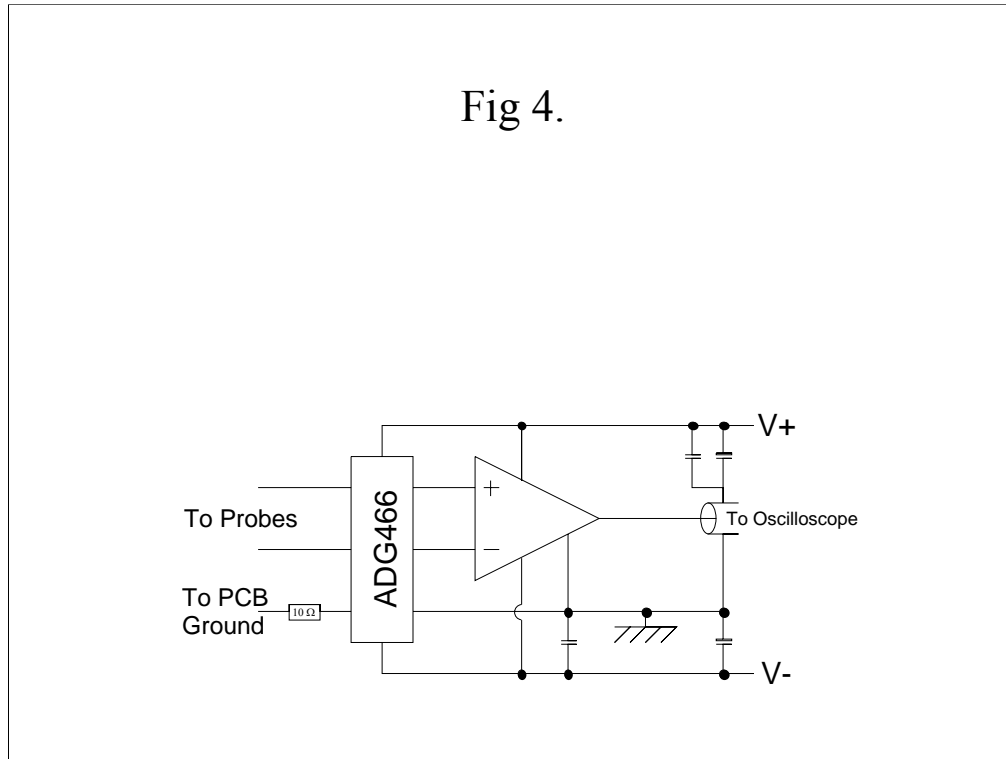
All op-amps and in-amps have input bias current. The bias currents in the inverting and non-inverting inputs are not exactly equal and generally flow in the same direction in both inputs. There must therefore be a current path from the in-amp inputs to a potential somewhere between the V+ and V- supplies. This is provided by the connection of the PC board ground to the reference terminal of the in-amp which is shown in the diagram. Of course this does create a potential problem – if there is a common ground connected to the system under test and the oscilloscope then this common-mode bias connection may create a ground loop which is not present when the test equipment is absent, and thereby introduce ground noise which corrupts the measurement.

The simplest way of preventing this problem is to isolate either the device under test (DUT) or the oscilloscope, and power the isolated device from batteries or an isolated power supply – but most of the time this is not necessary. The 10 Ω resistor in series with the connection limits ground loop currents and allows us to test it. (The resistor is too low in value to be likely to introduce any problems on its own account.) If the probes show a voltage (AC or DC) across this resistor then a ground current is flowing which is not present except when the test equipment is present. Since we know the value of the resistor we can calculate the current and determine if it is likely to present any problems to our measurements. If there is a potential problem we can use batteries or isolated supplies to avoid it.

The absolute maximum ratings of the AD620 input require that [A] the potential on either input may not exceed the supplies, and [B] the maximum differential input may not, in any case, exceed ± 25 V. If either of these conditions is broken the AD620 may be damaged. If the AD620 is used in the circuit shown in Fig 3 the inputs are unlikely to see damaging values, but if it is used at common-mode voltages away from ground the absolute maximum ratings must be carefully observed.

If there is a risk of input over-voltage there are several possible fixes. The first is to use an in-amp which is protected from input over-voltage. The AD524 has input protection which operates even in the absence of power on the device. It will sustain over-voltage of more than 30 V when powered off. But it has worse noise and higher supply voltage and current requirements than the AD620.

Fig 4.



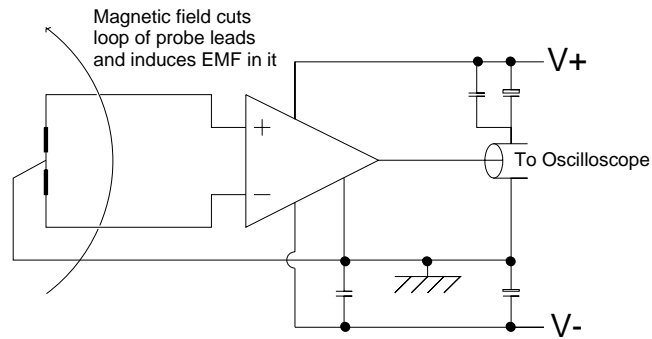
A more complex arrangement using protection circuitry in front of the AD620 is shown in Fig 4. The ADG466 is a 3-channel *channel protector* which uses protected analog switch technology to isolate its inputs and outputs under fault conditions. When power is off the input and output terminals are isolated. When power is present each input is connected to its corresponding output through a resistance of a few tens of ohms *unless* the voltage on the channel is outside the supply – in which case the input and output of the affected channel are isolated from each other.

This arrangement will protect the in-amp from fault voltages of ± 40 V. It will not protect it from electrostatic damage (ESD) or, if it does, only at the cost of damage to the channel protector. It is important, therefore, when using any of these test systems, to ensure that the ground of the tester is connected to the PCB ground *before* the probes are touched to the board.

To measure DC and LF ground noise between two points on a PCB the test system should be set up as discussed above and both probes touched to one of the measurement points (it is not sufficient just to touch them to each other as this does not allow bias currents to flow – they *must* connect to the PCB or some other node with a connection to the centre rail of the in-amp power supply as well). Since the two probes are short-circuited together they will be at the same DC potential and the vertical shift control of the oscilloscope can be used to bring the trace to the centre of the screen, trimming out any offset.

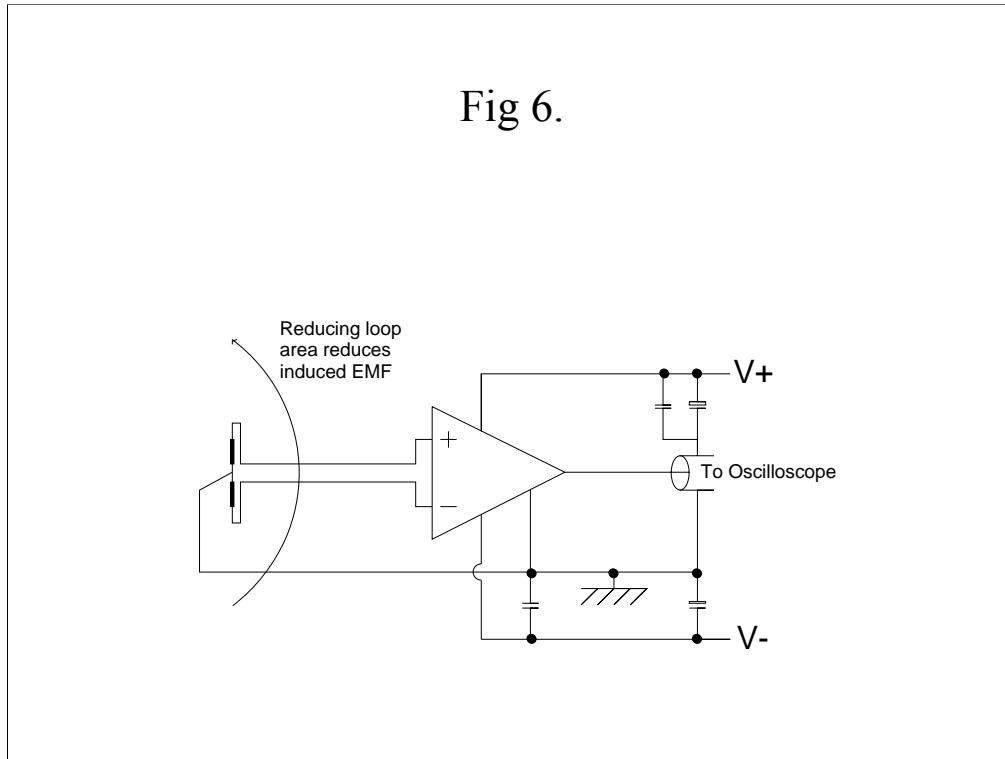
Leaving one probe in place the other is moved to another measurement point. Any shift in the trace position represents a DC shift in the voltage between the probes. Knowing the gain of the amplifier and the sensitivity of the oscilloscope we can calculate the voltage between the test points.

Fig 5.



If, in addition to the DC shift, there is an AC component to the oscilloscope display this may represent an AC voltage in the ground plane. But there may be another cause. To determine if the observed AC represents a signal in the PCB ground the two probes must be connected to the same test point again. If the AC is unchanged it is obviously not present in the PCB ground – the only other possible source is a voltage produced by stray alternating magnetic fields interacting with the leads to the test probes as illustrated in Fig 5.

Fig 6.



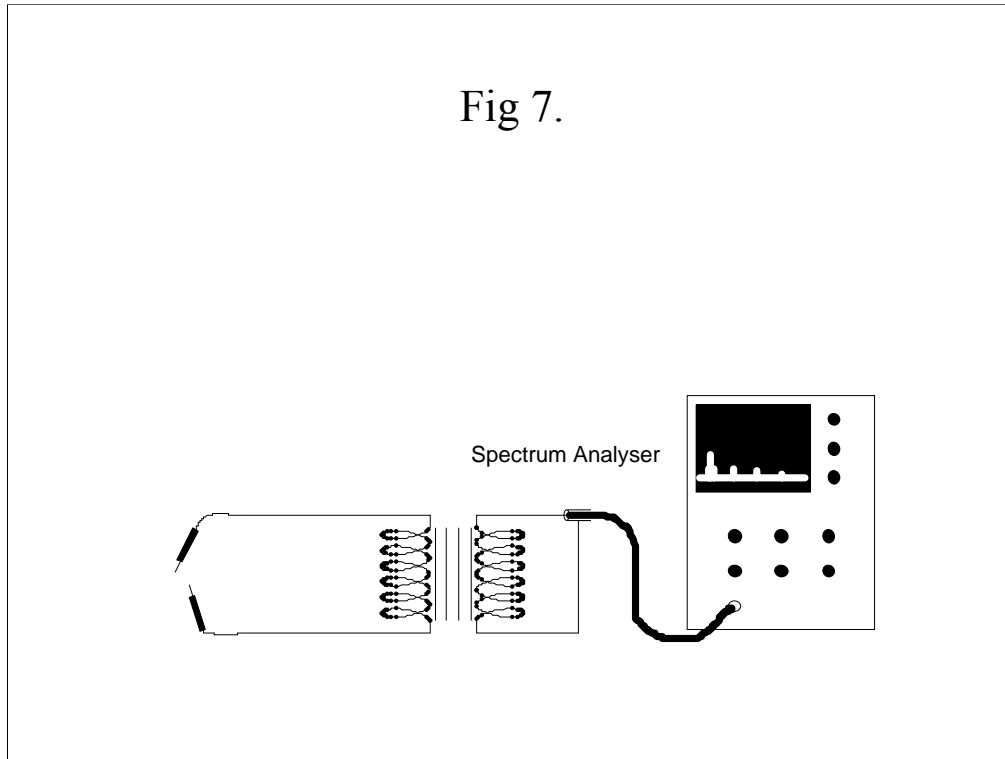
It is obvious that this induction can be prevented either by eliminating the varying magnetic field or by reducing the loop area. The latter option is usually simpler and is shown in Fig 6. The probe leads are simply rearranged to minimize pick-up of signals (twisting them is the best policy, but this is not always practicable).

Instrumentation amplifiers are not, of course, free from noise. The AD620 has a little over $1\text{ }\mu\text{V}$ r.m.s. input referred noise when used with a gain of 1,000. This means that the oscilloscope trace will not be a fine line but a fuzzy line several mV wide (referred to the oscilloscope input). Nevertheless it is perfectly possible to observe DC shifts of under a microvolt at the in-amp input using this test set-up, and AC signals little greater if they can be synchronized to the oscilloscope time base. It is impractical to view AC signals under two or three microvolts r.m.s. unless the time base can be synchronized to them.

The AD620 has a bandwidth of 12 KHz at a gain of 1,000. If wider measurement bandwidth is necessary either lower gain must be used (its bandwidth is 120 KHz at $A=100$) which entails reduced sensitivity, or a wider band in-amp, such as the AD524 with a bandwidth of 25 KHz. But in-amps are low frequency devices and cannot make high sensitivity measurements above a few tens of KHz. For that we must use different techniques.

Amplifiers do exist with high CMRR and wide bandwidth, but they do not have very high gains. If a sensitivity of 50 or $100\text{ }\mu\text{V}$ is adequate the AD830, which uses a different architecture from the LF one shown in Fig 1, may be used from DC to several MHz, and faster devices with similar architecture are likely in the future. But where it is necessary to measure low-level ground noise at tens or hundreds of MHz a different approach is needed.

Fig 7.

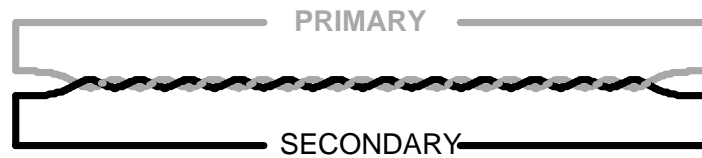


This uses broadband transformers to provide isolation and common-mode rejection. The general principle is the same – a pair of probes are moved around the ground-plane and measure the voltage between them. The difference is that there is no active device between the probes and the testgear, simply an isolating transformer. A transformer, especially a broadband transformer, rarely has a high voltage gain so the oscilloscope should be replaced with a spectrum analyzer, which is more sensitive. Of course its display is in the frequency domain instead of the time domain and may be slightly more difficult to interpret, but this is not a major problem. The arrangement is shown in Fig 7.

Since the transformer is a passive device there are no bias current requirements, and hence no need for a common ground. Of course this arrangement will only make high frequency measurements – it does not work at LF or DC.

If the ground noise is likely to be at a known frequency, or a narrow band of frequencies, the transformer will be quite simple – a 1:1 transformer having low loss at the frequency of interest. But in most systems it will be necessary to measure ground noise over a wide range of frequencies and a low-loss broadband transformer will be required. These may be bought quite cheaply from a number of manufacturers, including Mini-Circuits and Anzac (choose the cheapest 1:1 transformer whose frequency range equals or exceeds the range needed – power handling is not important), or they may be home-made quite easily.

Fig 8.

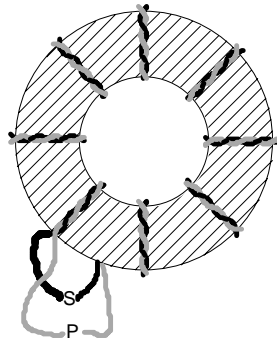


The best design is a transmission-line transformer using the basic principles described by Ruthroff as long ago as 1959.^[1] The primary and secondary are a length of transmission line, made of a twisted pair of insulated copper wires a fraction of a wavelength long at the highest frequency of interest. The transformer primary connections are made to the opposite ends of one of the pieces of wire, the secondary connections to the ends of the other. This transmission line is wound on a ferrite toroid or two-hole ferrite block using a ferrite appropriate for the lowest frequency of interest. With suitable wire-length and choice of ferrite it is possible to have a frequency range of well over 100:1. The basic designs are shown in Figs 8 & 9.

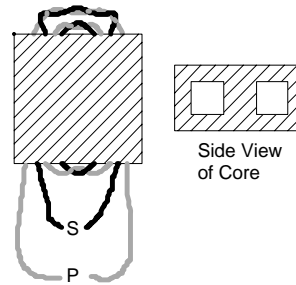
^[1] Ruthroff, C.L., "Some Broad-Band Transformers," Proceedings of the IRE, Aug 1959, pp. 1337-1342.

Fig 9.

BROADBAND TOROIDAL
TRANSFORMER
(Ruthroff transformer)



BROADBAND TRANSFORMER
IN TWO-HOLE FERRITE BLOCK



These two techniques, DC/LF and HF, between them allow us to measure the ground noise on a PCB over a wide range of frequencies and discover many sources of misbehavior. They are simple and easy to use but very powerful.

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Halloween 2001