

Grounding and Shielding Techniques for Large Scale Experiments

Marvin Johnson, Fermilab

Abstract-- The D0 detector has shown excellent common mode noise performance across all sub detectors. This talk will describe the detector, the noise performance and the methods that we used to achieve them. I will focus on the general principals rather than the specific implementations. I will also discuss some new work that we are doing with carbon fiber composites.

I. INTRODUCTION

The D0 detector is a large, multipurpose colliding beams detector at Fermilab. Fig. 1 shows the main parts of the detector. This talk will concentrate on the calorimeter and the silicon detector. The calorimeter is a precision analog device with 15 bit resolution ADC's and the silicon detector has severe constraints on mass so many conventional noise reduction methods are difficult to apply.

The D0 calorimeter is a large liquid argon calorimeter consisting of 3 independent cryostats. Each cryostat is about 6 meters in diameter, 3 meters in length and contains roughly 16,000 channels. The preamps are located on top of each cryostat and send single ended signals about 15 meters to a counting house located under the detector. Here a correlated double sample measurement is made and the difference is sent to a second counting house about 60 meters away. At this point the signals are digitized in VME crates to 15 effective bits. Common mode noise was measured by computing a correlation coefficient over 4096 channels and no measurable noise has been found. This gives an upper limit on the common mode noise of 1 part in 2^{17} or about 106 db down from the maximum signal.

The D0 silicon system is a fairly conventional silicon detector with a mix of single and double-sided detectors. There are 912 ladders in the detector with around 800,000 channels. Readout is via the SVX 2 chip. The common mode noise is measurable and it is around 1000 electrons. The detector capacitance is 12 pF so this is a 10 μ V signal. The source of this noise is not yet known.

How do we achieve such good noise performance on a detector that weighs 5600 tons and occupies a volume of 1700 cubic meters? There are only a few broad principles involved in effective low noise design. It is merely a matter of applying these principles and paying attention to the details. Books by Ott[1] and Morrison [2] are good references for noise reduction techniques.

The next section will describe some general principals for low noise design and the following sections will give examples from the D0 detector.

II. ELEMENTS OF A LOW NOISE DESIGN.

The most important principle is that current follows the path of least impedance. The key here is impedance which involves inductance and capacitance as well as resistance. Inductance is often overlooked and is very important. Consider a simple structure consisting of two 1 cm diameter rods that are 1 meter long and spaced 1 cm apart. At 30 MHz, the impedance from the inductance of one rod equals the impedance from the capacitance between the two rods. Thus, if one rod were part of a noisy ground and the other part of a precision instrument (silicon detector for example), potentially half the noise would be transferred to the clean system. Of course, this depends on the impedances of the rest of the circuit but it is quite unlikely that no noise is transferred.

The formula for the capacitance of a parallel plate capacitor is

$$C = 8.85 \times 10^{-12} \frac{\epsilon A}{d}$$

where A is the area of the plates, d is the separation of the plates and ϵ is the relative permittivity of the material between the plates ($\epsilon=1$ for air). The formula for the self inductance of a straight, round wire is[3]

$$L = 2 \times 10^{-7} \ln \left[\frac{2s}{r} - \frac{3}{4} \right]$$

Work supported by the U.S. Department of Energy under contract No.

DE-AC02-76CH03000

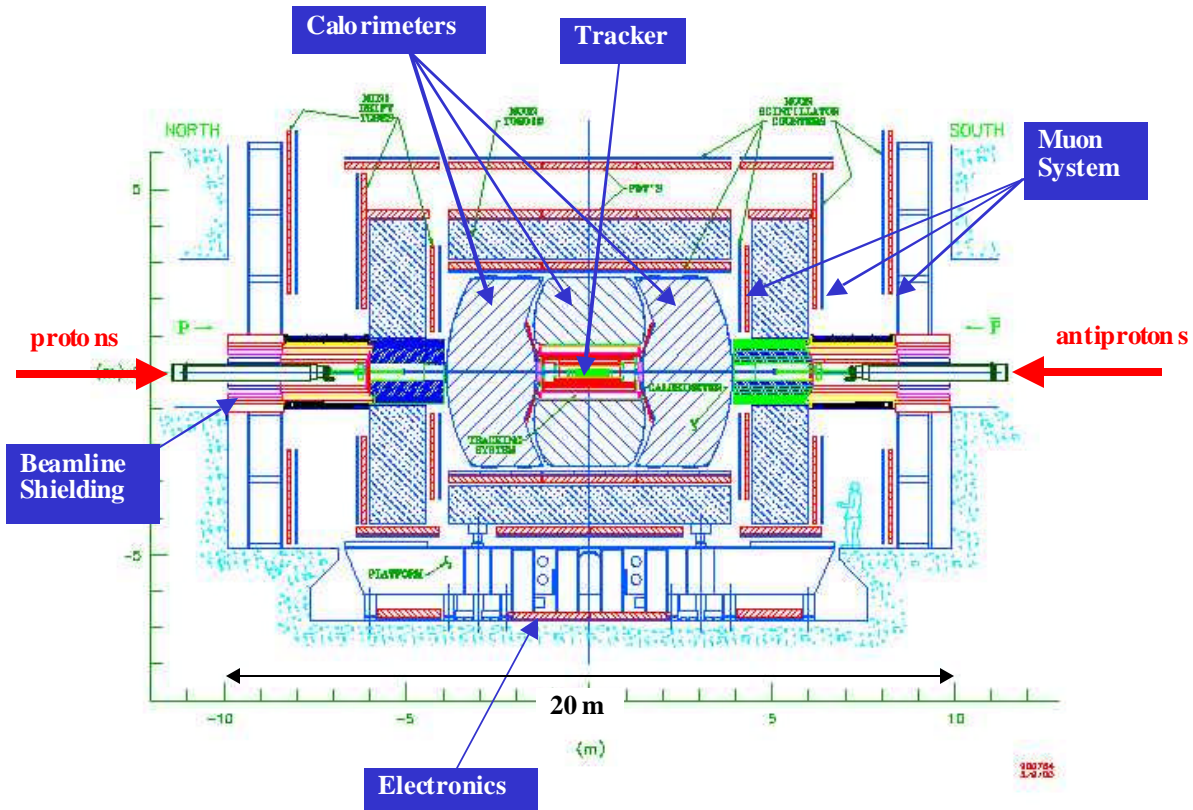


Figure 1. Side view of the D0 detector showing the main sub detectors. The platform area is under the detector where the electronics is located. The ground plane is on the floor of the electronics area.

where s and r are the length and radius of the wire and μ is his relative permeability of the material. All units are in SI. For rectangles an approximate formula is

$$L = 2 \times 10^{-7} \text{ sm} \left[\text{Log}_e \left(\frac{2s}{b+c} \right) + \frac{1}{2} \right]$$

where b and c are the width and length of the rectangle. Wide, thin sheets have much lower inductance than round or square objects

The second principle is that current always flows in complete circuits. Whenever analyzing a system, one needs to find the complete path and all the paths. An area where this is often overlooked is in front end designs where people worry a great deal about the path between the detector and the preamp but ignore completely the ground current path back to the detector. For example, in a proportional wire chamber, the preamp amplifies the signal between the cathode and the anode and is usually attached to the anode. There must be a a low impedance path from the preamp ground to the cathode. If this is overlooked, the return current may have to go all the way to the high voltage supply and back again. If the path length is long enough, the added phase shift could cause the preamp to oscillate. Any unnecessarily added path increases the likelihood of noise pick up and should be avoided.

The third principle can be thought of as a property of inductance or that nature seeks the minimum energy state. I will explain it using inductance. Since the inductance of a circuit is in general proportional to the area enclosed by the circuit, as the frequency increases, the current will flow in the circuit with the least area. Typically frequencies for this to occur begin in the few hundred KHz range. This means that there may be a good ground plane between two points, but if the signal flows some distance from the ground plane, the return current may not be in the ground plane at all.

The fourth and last principle is that if one has a set of coaxial conductors, any current flowing in the coaxial outer shell will be induced in the inner conductors by transformer action. The inner conductors can be anywhere inside the shell – they do not have to be coaxial. This principle is strictly true only for round outer conductors but it is a good approximation for many common structures such as cable trays.

Another point which is not a general principle but is often useful in practice is that a noise source is usually not a voltage source. That is, it cannot supply an infinite amount of current. Often a simple filters will do a good job of eliminating noise by loading down the noise source.

In applying these principles, the goal is to shunt the noise away from the signal carrying conductors. The next section describes how we applied these principles to achieve the good noise performance in D0.

III. EXAMPLES FROM D0.

A. AC Power Distribution

Power distribution plays a very important role in detector design. It is best to put in a separate substation for detector power. High frequency power does not flow readily through the inductance of a transformer coil. However, in order to get high power efficiency, transformer makers position the primary and secondary coils close together so there is a large capacitive coupling both within and between the primary and secondary coils. We usually don't care about capacitive shorts within the primary or secondary since they just shunt the power to their respective grounds. However, capacitive shorts between the two cause unwanted noise transfer. Transformer makers know all about this and they make transformers with single and double faraday shields. A double faraday shield encloses each coil in a metal box (usually copper mesh to avoid large eddy currents). The primary shield is then connected to the outside world ground so that incoming noise on the power cables flows back to an external ground. Similarly, the secondary shield is connected to the secondary ground. This keeps any locally generated noise confined to that system. A single faraday shield has just one metal box – usually around the primary.

D0 has two 1.5 MVA substations to power the D0 complex. One of the substations is mostly dedicated to detector power and the other for everything else. These are not faraday shielded transformers so the isolation is not large. However, the cables from the substation to the detector transformers are of order 100 meters so there is some filtering from the cable inductance. Cable inductance filtering is discussed more fully in the section on magnet power supplies.

D0 employs six 150 KVA transformers to power the experiment. These were meant to be double faraday shielded ones but, due to a vendor error, there is only a single faraday shield. Fig. 2 shows the transformer configuration that we designed for D0. The actual system differs only by removing the secondary faraday shield.

Three of these faraday shielded secondary transformers are located in a small counting house located directly below the detector (called the “platform”) and 3 are located on a counting house outside the radiation wall (called the “moving counting house”). No attempt is made to isolate functions on the platform. The first two floors of the moving counting house are dedicated to digital electronics while the third floor is used for analog readout.

There is one transformer per floor of the counting house and all power for the floor including such things as lights and air conditioning comes from this transformer. This allows a fairly clean separation of power. Of course, the building shares a common ground but we observe that the analog floor has very little noise from the 2 digital floors.

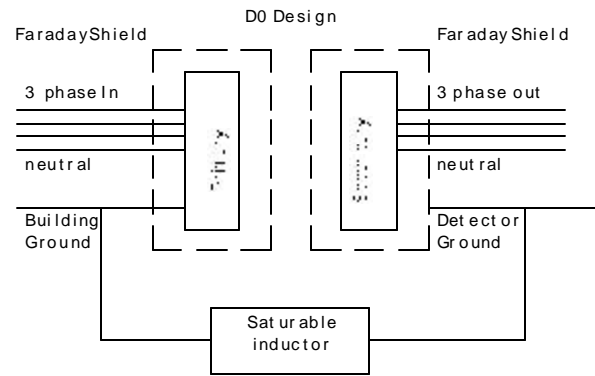


Figure 2 Diagram of a double faraday shielded transformer that was planned for D0. The as built design has no secondary shield

D0 has also totally isolated the detector from building ground for high frequency signals. That is, there is no direct connection for high frequencies between building ground and detector ground. All signals are either optical or transformer isolated. Of course, there must be a safety ground so that no one is injured if there is a transformer failure. This is provided by a saturable inductor which is connected between the 2 grounds. The inductor has about 1 mH inductance at low currents. It starts to saturate at 10 amps and has only 80 μ H of inductance at full saturation. D0 employs 2 of these inductors for redundancy. With these inductors open, the detector has about 45 nF of capacitance to the building ground. This is about 7 ohms at 500 KHz. We have made considerable effort to maintain this isolation but I think that it is no longer completely isolated. Even if it is not truly isolated, the paths for ground currents from the accelerator tunnel to pass through the detector to the D0 complex are very limited and this removes another potential source of noise.

B. Magnet Power Supplies

Magnet power supplies are often filtered with series L and a parallel C. This works well for 720 Hz but not for high frequencies. Again, the turn to turn capacitance in a large, high current inductor shorts out the inductance. D0 has employed 2 different methods for high frequency filters for the magnets. The first utilizes the magnet buss itself. The path from the power supply to the detector is about 100 meters so the buss has an inductance of about 1.5 mH. Attaching large, oil filled capacitors at the midpoint of the buss and next to the detector on both the supply and return lines eliminated almost all of the power supply noise. Note that there is no specific return path to the power supply for this high frequency power. The building is made of concrete and steel with a great deal of steel reinforcing rod in the concrete. We connected the ground of the filter capacitors to the building ground and attached the power supply to the building steel with a low inductance path.

For D0's superconducting solenoid, we went to a more conventional air core coil arrangement. The turns are widely separated so that the turn to turn capacitance is small and there is no core to capacitively short out the turns. This magnet has been in use for the past year and we have no indication of any noise from it. During installation, we made provision to use the buss filtering method but, so far, it has not been needed.

C. Low Voltage Power Supplies

Conventional wisdom indicates that linear supplies give the best low noise performance. Initially, D0 went this route. We developed a custom 3 phase linear supply with excellent noise performance. Unfortunately, its efficiency was just over 50% and we had to do all the work of building and maintaining them. We wanted to try some commercial switching supplies but did not know what a reasonable set of specifications would be. So, we hired a firm that measures the noise parameters for commercial manufacturers to measure some of our linear supplies. We then selected commercial supplies that exceeded these specs and we have not had any problem so far.

D. Ground Planes and Ground Reference.

Ground planes are usually an essential element of a high performance circuit board. They provide a reference for single ended signals and act as a low impedance return to the source for noise power generated on the board. They also provide some level of shielding between circuit sections. These same functions are needed on a detector. Like designing a board, it is important to determine the ground references for your detector at the early design stage. At optimum choice can often lead to very low noise systems.

As mentioned earlier, the output of the calorimeter preamps is single ended. We need to add many channels together to get the energy in a jet of particles so it is important that no noise current flow on the ground wire from each calorimeter output. We used several methods to achieve this. One of them is to reduce the ground voltage as much as possible between the preamps and the electronics under the detector by connecting everything to a low inductance ground plane.

We chose the floor of the platform under the detector as the fundamental ground reference for the calorimeter. We installed a 1/16 inch thick solid copper ground plane under the entire detector (12 by 12 meters!). This plane covers about 90% of the floor area and it was welded together and to the steel of the detector support structure. There are 72 racks in the platform area with 36 being used by the calorimeter electronics. Each rack is connected to the ground plane with a 6 inch wide sheet of 1/16 inch copper strip.. One side of this strip is welded to the ground plane and the other is welded to a tin plated copper block. This block has several holes in it and is fastened to the rack at the bottom rear. This provided a convenient ground point for rack electronics.

Note that all connections are welded. Rivet connections are quite inductive and should be avoided if possible. Also, if the material is aluminum, the aluminum oxide layer at the connection may substantially increase the resistance of a riveted connection.

For the calorimeter racks, we were concerned that the inductance of a ground braid between the back plane and the copper block would lead to additional noise. So, we installed about a 25 cm wide copper sheet along each side of the rack. The bottom was welded to the ground plane. We then extended the analog ground reference on each back plane to the sheets and made a good, low inductance connection.

The calorimeter preamp boxes are mounted on top of the calorimeter about 10 meters from the ground plane. Since the structure is a massive mechanical device that is welded together, we relied in part on this mechanical structure to link the preamps to the racks. We also made closed cable trays out of tin plated aluminum. The trays are totally enclosed and extend continuously (welded together) from the preamps to the racks.

The preamp assemblies are also made out of tin plated aluminum and are mounted on a copper sheet that covers the top part of the calorimeter. This copper sheet serves as a local ground plane to provide a low inductance path between the preamp grounds and the high voltage system. All the electronics associated with the preamps are connected to this plane.

Each of the floors of the counting house outside the radiation wall also has a ground plane. We selected a mesh ground plane consisting of 10 cm wide strips spaced 60 cm on center. This was installed by a commercial firm specializing in computer room installations. All the junctions are welded.

The signals between the area under the detector and the moving counting house are also single ended so we had the problem of minimizing the potential difference between the two structures. This was done by installing a covered copper cable tray that connected to the detector ground plane on one side and the moving counting house one on the other. The horizontal part of this tray was 2 meters wide, 30 cm thick and 6 meters long. Since inductance depends on the log of the length to width ratio, this path has an impedance of 8 ohms at 500 KHz.

E. Shielding

A large diameter cylinder has lower inductance than a wire. A closed cable tray also protects cables from pickup. Thus, we used enclosed cable trays from the preamp boxes to the racks on the platform. Ground currents flowing on these trays will induce noise on the wires inside by transformer action. The trays are large so that the signals to entire crates are within a tray. The entire crate moves at once so we effectively have a differential input for tray noise. This system works

well. When a cover is removed from one of the trays, that set of preamps has higher noise than all the rest.

F. Silicon Detectors

Silicon detectors have some special problems. Typical signals are 24000 electrons which is 0.3 mV. Even a modest signal to noise ratio of 10 means that common mode noise must be kept to 30 μ V. A fairly common problem for common mode noise is to have some conductor under the silicon (mounting bracket, cooling tube etc) which is connected to a different ground than the readout chip. Since the input amplifier is at virtual ground (at least for AC signals), power flows from one ground to the other through the amplifier. A slightly different mechanism occurs when the readout chip is mounted on a circuit board glued to the sensor. The sensor is now between the ground plane and the grounded structure, i.e., between 2 plates of a capacitor. Again, any current flow through this capacitor will be picked up by the input amplifier.

The solution to this problem is to locally short out this capacitor. This means tying the amplifier ground both to the bias line through a capacitor (to provide a current return path) and to the support structure. These connections are often mechanically difficult to make. However, if they fail in service, the noise may make that detector element useless.

One must also take precautions to minimize the total ground current. A particularly important area is when a silicon detector is read out from both ends. If the support or cooling structure is conductive and tied together, the ground loop formed probably encloses many sources of noise – perhaps even a magnet coil. The solution is to break the conducting paths where the readout changes sides. This must be an AC as well as DC break and this is often difficult because it usually means separating the sensors. Most likely, complete isolation is not possible.

At D0, the silicon detector is split at the center and it is fully ground isolated from the calorimeter. So far, the central calorimeter sees no noise from the silicon system and we have only 1 count (1000 electrons) of common mode noise.

IV. CARBON FIBER COMPOSITES

Carbon fiber support structures are being increasingly used in detectors. Carbon has a conductivity that is about 50 times less than copper but it can have surprisingly high conductivities at high frequencies (see below). We have undertaken a careful study of the AC properties of carbon fiber composites. The support structure of the new silicon detector is an all carbon fiber composite structure so we need to understand how to ground it properly.

For the first test we made a parallel plate capacitor out of two 6 inch by 6 inch plates of copper separated by a 1/4 inch piece of G10 fiberglass laminate. We measured the capacitance as a function of frequency with a HP4193A vector impedance meter. We then replaced one of the copper plates with one made from carbon fiber laminate. The carbon fiber

was carefully cleaned but no other preparation was done. We then attached one of the impedance meter leads to the carbon fiber with a piece of copper tape. We varied the size of this copper tape from 1 square inch to 36 square inches (the latter completely covers the carbon fiber piece).

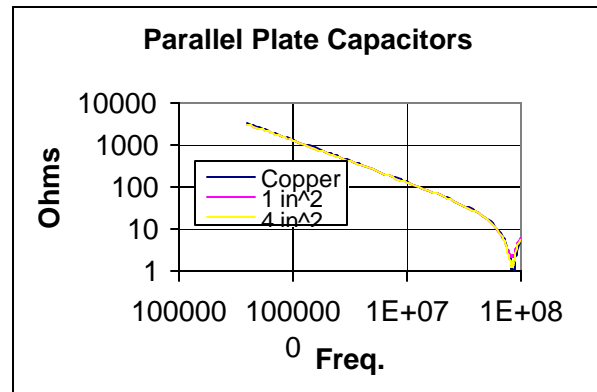


Figure 3. Capacitance of a parallel plate capacitor with 2 copper plates (cu data) and one with 1 copper and 1 carbon fiber plate. The probe was attached to the carbon fiber with either 1 or 4 square inches of copper tape

The results are shown in fig. 3 for the 1 and four square inch copper tape coverage along with the all copper curve. For most of the plot there is absolutely no difference. The only difference is at the minimum where the phase shifts through 0. At this point the impedance is real (phase shift passes through 0). The resistance of these points is plotted in fig 4 as a function of the area of the copper tape. Note that this function reaches a plateau after about 4 square inches (11% of the area.).

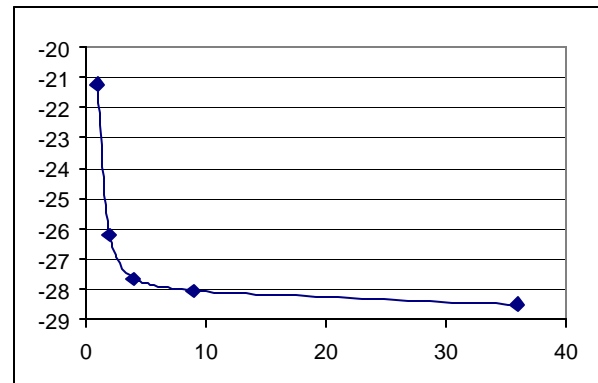


Figure 4. Capacitance of a parallel plate capacitor with 1 copper and 1 carbon fiber plate. The vertical axis is the db attenuation of the signal at 0 degree phase angle, i.e., the point where the resistance is real. The horizontal axis is the area of copper foil that is covering the carbon fiber. The point at 36 square inches represents complete covering of the carbon fiber by copper.

Since copper has too high a mass for silicon detector applications, we did the same experiment using 12 micron Al foil. This foil was placed at the bottom of the mold and cured directly with the carbon fiber material. We had samples made that ranged from 1/4 to 4 square inches. These were bonded to a 10 by 2 inch piece of carbon fiber which was assembled

into a capacitor using a copper plate and 1/4 inch thick G10. The results of the vector impedance meter are shown in fig. 5. Again, the size of the aluminum contact has no effect on the impedance except at the point where the impedance is real and this affect is quite small.

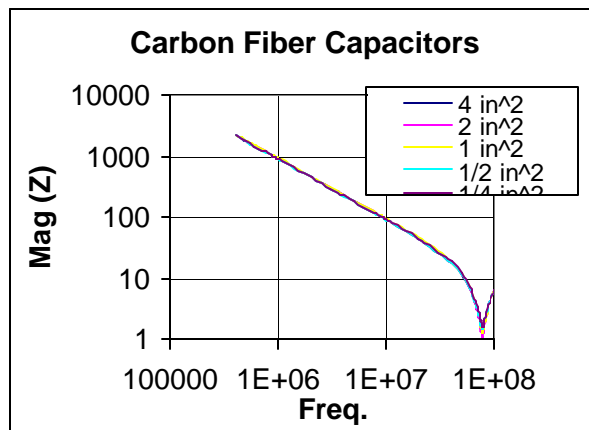


Figure 5. Capacitance of a carbon fiber –copper capacitor with aluminum connections to the carbon fiber. The al connections range in size from 1/4 square inches to 4 square inches.

Why is carbon fiber so good a conductor while carbon itself is very poor. My hypothesis is that it is due to the fact that the carbon is confined to fibers in a non conducting matrix of epoxy. The skin depth of copper at 1 MHz is 66 microns which is the thickness that one uses to calculate the resistance. Skin depth is caused by eddy currents which depend on the conductivity. Since skin depth is proportional to the square root of the resistivity, carbon would have a skin depth about 7 times larger than copper. However, the carbon fiber structure will eliminate most of the eddy currents so the skin depth is likely much larger. If it were 7 times larger than for pure carbon, the resistance would be the same. Fifty times 66 microns is 3.3 mm which is somewhat less than the thickness of the sample.

There is some additional evidence for skin depth from the phase shift of the signal measured by the impedance analyzer. At low frequencies, the copper capacitor has a 90degree phase shift as expected. The copper carbon fiber one has only 88 degrees. If the material thickness were equal to the skin depth, some of the primary signal would be transmitted through the plate. This signal would then add to the signal shifted by the capacitor and reduce the phase shift which is what we observe.

V. CONCLUSION

D0 has achieved quite good noise rejection for common mode signals. None of the techniques are particularly expensive or difficult to implement provided they are done at the design stage of the experiment. Retrofits are most likely impossible.

There are often different ways to achieve the same goals but some of the methods may not be compatible with one

another. Therefore, I think that it is better to have a single person responsible than a committee.

VI. ACKNOWLEDGEMENTS

The work on carbon fiber was done in collaboration with Michael Matulik and Breese Quinn.

VII. REFERENCES

- [1] Henry W. Ott, *Noise Reduction Techniques in Electronic Systems*, 2nd ed., New York: John Wiley & Sons, 1988
- [2] Ralph Morrison, *Grounding and Shielding Techniques in Instrumentation*, 2nd ed., New York: John Wiley & Sons, 1977.
- [3] Frederick W. Grover, *Inductance calculations*, New York: Dover, 1946, pp33-35.