Application Note:
Noise Reduction Techniques

10 December 2024

The first problem encountered by any experimental electrophysiologist is reducing noise. While Intan amplifiers have a low input-referred noise floor of 2.4 μV_{rms} (about 14 μV peak-to-peak), this electronic noise is rarely the limiting factor when measuring small biological signals in real experiments. First-time users often expect to see flatline "zero" waveforms when they observe signals from headstages with no electrodes connected, or headstages connected to electrodes but not inserted into tissue or saline. Instead, they typically see large 50 Hz or 60 Hz sinusoidal signals on all channels. This is unfortunately the usual situation in electrophysiology recording.

Reducing the pickup of external interfering signals – which we will simply call "noise" in this document even though it is more accurately characterized as "interference" – is often the most difficult part of setting up an electrophysiology rig. In this Application Note, we will provide the reader with an understanding of common sources of noise and some practical tips for minimizing them.

Electric Fields and Faraday Cages

The most familiar mechanism for interfering signals to couple into sensitive amplifiers is through electric fields. The AC power wiring in the walls of most buildings is the dominant source of noise that electrophysiologists must contend with. Depending on which country your lab is based in, these wires oscillate either at 50 Hz or 60 Hz with high voltages between 110 V and 240 V. These voltage levels are a million times larger than typical extracellular signals in the brain, and they lie in the upper end of the local field potential (LFP) frequency range.

The oscillating voltages on these wires create AC electric fields that couple to other conductors through the air or other intervening insulators. One way to model this coupling is as a **voltage divider** using capacitances (see Figure 1 below). There is a very small capacitance between the noise source (the power wiring in the walls) and the amplifier input. (Even with no electrode connected, the connector on the headstage or even the pad on the Intan microchip will pick up electric fields.) There is a second capacitance between this amplifier input and the amplifier ground. In our Intan microchips, there is about 12 pF of capacitance from each amplifier input to ground, internal to the microchip. (Remember, 1 pF = 10^{-12} F.) These two capacitances form a voltage divider that attenuates the large voltage from the power wiring when it reaches the amplifier input. But does it attenuate it enough?

The equation for a capacitive voltage divider is $V_2 / V_1 = C_1 / (C_1 + C_2)$. (This differs from the equation for a *resistive* voltage divider because the impedance of a capacitor is proportional to 1/C while the impedance of a resistor is proportional to R.) In the case of Intan amplifiers, C_2 = 12 pF, plus maybe a few more picofarads of parasitic capacitance to ground from the printed circuit board (PCB), connectors, and any electrodes that may be connected. But it is on the order of 10^{-11} F in any case.

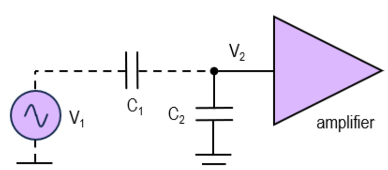

Figure 1. A capacitive voltage divider models noise pickup from electric fields.

To get an idea of these tiny capacitances in practical circuits, if you take two insulated wires and twist them together for 2-3 cm, the capacitance between these wires will be on the order of 1 pF for typical insulation thicknesses. If you move these wires farther apart, the capacitance will fall off roughly as the reciprocal of distance. But if you make either wire longer, the capacitance will increase, and the power wires in the walls are very long. In most cases the value of C_1 will be incredibly small, because our experiment will a considerable distance from the power wiring. But we have very sensitive amplifiers that can see voltages in the microvolt range. So even if $C_1 \approx 0.0001$ pF, we have $V_1 \approx 200$ V so V_2, the voltage at the input of the amplifier, will be on the order of 2000 μV. This is ten times larger than typical extracellular action potentials, and 1000 times larger than the amplifier noise floor!

Luckily, it is easy to block electric fields using a **Faraday cage**. A Faraday cage is the name given to any conductive enclosure that surrounds a sensitive experiment and serves to block external electric fields. The Faraday cage is tied to ground, and this provides a new termination point for C_1, so the interfering signal never reaches the amplifier.

Faraday cages may be purchased or hand-built in the lab. A cardboard box covered in aluminum foil is equally effective at stopping electric fields as an expensive wire-mesh cage, though the wire mesh is more convenient to use because it is mostly transparent. Small holes in the conductive material do not matter, but it is important to cover all sides of the experiment, even the bottom. The Faraday cage should be one continuous conductor. To be effective, it should not be electrically connected to anything *inside* the cage. It should be connected to a ground point *outside* the cage, as shown in Figure 2 below. If you are using the old Intan RHD USB interface board, connect the cage to any of the GND terminals on the periphery of the board. If you are using the newer Intan RHD recording controller or RHS stim/recording controller, connect the cage to either the green or black terminal (CHASSIS GND or I/O GND) on the back panel. Or you can connect the cage to another ground point in your lab. Experiment with different ground points and see which one works best. You don't have to use a thick wire for this connection.

The tissue, electrodes, and Intan headstages should be placed inside the Faraday cage. The Intan controller and computer (which generate digital noise and also have high-voltage AC power wiring) should be located outside the cage.

The GND terminal on the Intan headstage should be connected to the tissue via a ground electrode or skull screw, but this should not be connected to the Faraday cage or to any external ground. (If you leave the zero-ohm R0 resistor in place on the RHD or RHS headstage then REF is shorted to GND and you can just use one combined REF/GND electrode that connects to tissue.) Try to keep your tissue electrically isolated from the Faraday cage.

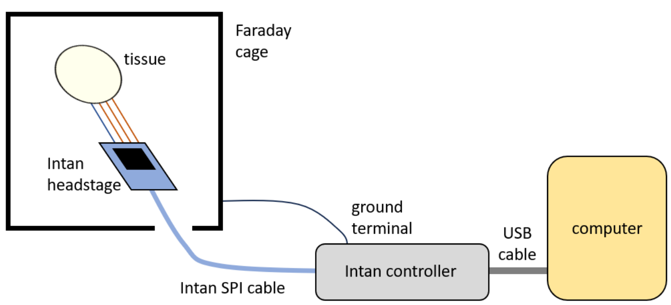

Figure 2. Recommended Faraday cage setup.

Some users are able to get good noise-free recordings without using a complete Faraday cage. Sometimes a conductive table underneath the experiment acting as a partial Faraday cage is sufficient. You can also experiment with different locations in your lab to see where interference is weaker. And you may find you do not need a complete Faraday cage if you follow the suggestions in the next section.

Magnetic Fields and Wiring Geometry

Faraday cages block electric fields, but they do not block low-frequency magnetic fields. The AC power wiring in the walls produces both electric *and* magnetic fields at 50 Hz or 60 Hz. The only way to block these low-frequency magnetic fields is to use heavy pieces of high-permeability "mu-metal" (a nickel-iron alloy) several centimeters thick. In practice, this is only done in magnetoencephalography (MEG) experiments.

The good news is that magnetic fields fall off faster than electric fields: as the cube of distance rather than the square. Magnetic fields are also sensitive to geometry: two parallel wires will couple through their mutual magnetic fields, but two perpendicular wires are independent.

The primary mechanism for noise coupling through magnetic fields is **Faraday's law** (which has nothing to do with Faraday cages; Faraday was a prolific scientist!). This states that when an electric circuit forms a loop and AC magnetic flux passes through that loop, then the changing magnetic flux will induce an AC voltage in the circuit. This is the basis of electric generators and transformers.

Figure 3 below shows a basic single-channel recording setup: an Intan headstage is connected to electrodes in tissue with two wires: a reference wire (which is often a combined REF/GND wire as mentioned above) and a signal wire. This creates a complete electric circuit. The geometry of these wires is important here. Trace the complete circuit from the headstage through the signal wire, to the tissue, and back through the reference wire to the headstage. Look at the area of this loop (the gray area shown in Figure 4). This area acts like a pickup antenna for any AC magnetic fields that pass through this loop. By Faraday's law, these magnetic fields are converted into AC voltages that appear at the input of the amplifier, superimposed on the signals picked up by the electrodes in the tissue.

This is a very common source of noise pickup in preliminary experiments when users are trying out an Intan system for the first time before moving to small integrated probes that connect directly to the headstage. Someone will rig up a couple of electrodes in a jar of saline and use long wires to connect the headstage to the electrodes, and then see large 50/60 Hz noise. The long wires usually create a large open loop that picks up lots of magnetic flux.

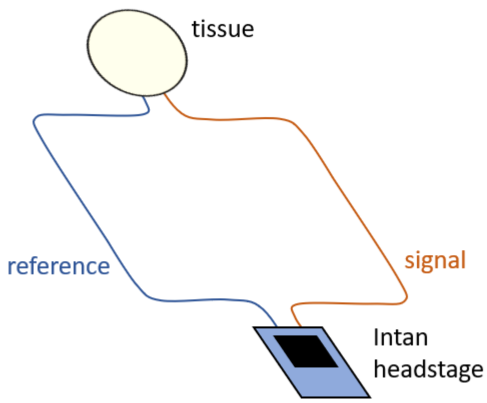

Figure 3. Typical single-channel recording setup.

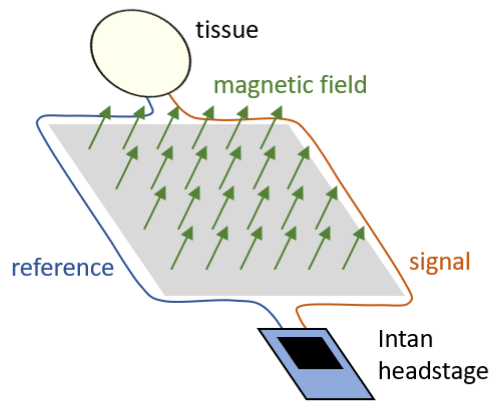

Figure 4. The large open loop area (in gray) is sensitive to AC magnetic flux (shown in green), which is converted to an AC voltage by Faraday's law.

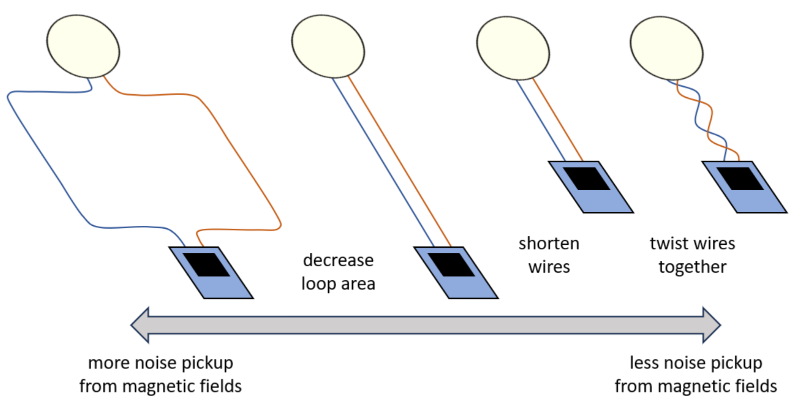

Figure 5. Reducing noise pickup from magnetic fields by changing wiring geometry.

The solution to magnetic field interference is purely geometric: reduce the loop area of your circuit. Figure 5 shows the three techniques you can use: decrease the loop area by bundling the wires close together, minimize the length of the wires between the headstage and electrodes (ideally this length should be less than 10 cm), and (optionally) twist the wires together to create small loops of alternating orientation so the magnetic field influences cancel out. If the first two techniques are followed it is usually not necessary to twist the wires. (Twisted pairs of wires are useful for recording from pairs of electrodes using the bipolar-input Intan RHD2216 chip.) Note that wires twisted together must be insulated to prevent them from shorting together.

Ground Loops

Magnetic fields also come into play with the phenomenon of **ground loops**. When setting up an electrophysiology rig you will have many different electronic devices: headstages, controllers, computers, sensors, and actuators. If these devices share electrical signals, they must have a common ground established between them. It is important to use a **star ground** geometry as illustrated below to avoid ground loops.

Why are ground loops bad? Because of Faraday's law (see previous section). Any AC magnetic field passing through the loop will induce an AC voltage on the circuit (see Figure 4). But in this case the circuit is ground! We want ground to be the same potential everywhere in our experimental rig, but if we create a loop then AC magnetic fields will induce voltage fluctuations that will vary across our ground wires.

Some people think this situation can be helped by using thicker ground wires to reduce the resistance, but resistance isn't the issue here; it is *inductance* that matters. And the inductance of a loop of wire is determined purely by its geometry. Ground loops would inject noise even if the resistance of the ground wires were zero. Due to finite inductance, the *impedance* of a wire is nonzero at AC signal frequencies even if its DC *resistance* is zero.

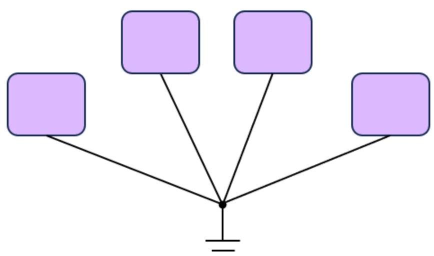

Figure 6. Star ground (good). There are no loops that can pick up interference from AC magnetic fields.

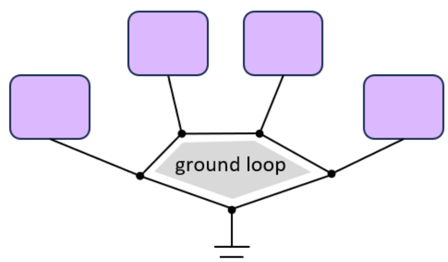

Figure 7. Ground loop (bad). Any AC magnetic flux passing through the loop creates voltage fluctuations in the ground wires.

Thermal Noise from Resistors (and Electrodes)

Resistors, or any resistive material, in series with a circuit produces **thermal noise**, sometimes called **Johnson noise**. The rms noise added by a series resistor R is given by

$$v_{n,rms} = \sqrt{4kTR \cdot BW}$$

where BW is the amplifier bandwidth and k is Boltzmann's constant ($kT = 4.12 \times 10^{-21}$ Joules at 25ºC). If we use 10 kHz as the maximum bandwidth normally used in Intan systems, we find that a resistance of 10 kΩ produces a noise level of 1.3 μV_{rms}, which is about half the noise floor of the Intan amplifiers. Most resistances associated with wiring, solder joints, and connectors will be a few ohms at most. The bottom line is that you do not need to worry about connector resistance or using thicker wires. You must get *well* into the kilohm range before noise due to series resistance becomes significant. Connectors only add noise to the extent that they pick up electric or magnetic fields due to their geometry.

You may wonder about noise from the electrodes themselves. After all, it is common to use electrodes with reported impedances of hundreds of kilohms or even megaohms. Based on the formula above, a 1 MΩ electrode would have a noise level of 13 μV_{rms}, or about 80 μV peak-to-peak. This is higher than noise levels actually observed. Real electrodes are not purely resistive. Most electrodes behave much more like capacitors when placed in tissue or saline, and capacitors do not produce thermal noise. By convention, electrode impedance is measured at 1 kHz, and usually the phase angle of this impedance is between -60º and -80º, indicating mostly capacitive behavior. (A pure capacitance has an impedance with a phase angle of -90º.) The actual series resistance of an electrode that generates thermal noise is some fraction of the reported electrode impedance.

Photoelectric Noise

Many neural probes used with Intan headstages are made from silicon, and silicon is extremely effective at converting light to electrical currents and voltages. Most incandescent, fluorescent, and LED lights flicker at twice the power line frequency, so this can introduce 100 Hz or 120 Hz noise into experiments. If you have followed all the recommendations above for reducing interference from electric and magnetic fields and still see noise at these frequencies, try blocking light from your probes or using a battery-powered flashlight if you need a light source.

Motion Artifacts

In experiments with freely-moving animals, motion artifacts can be a problem. Any movement of the electrodes relative to tissue will typically induce large electrical artifacts. The solution to this is to secure the electrodes firmly to the skull. If movement artifacts cannot be eliminated, you may wish to use Intan RHD headstages with integrated accelerometers so that you can at least flag moments of high acceleration as likely artifacts.

Notch Filters for Noise Reduction

Users of the Intan RHX software will have seen an optional **notch filter** that can remove 50 Hz or 60 Hz frequency components. Why bother with all these Faraday cages and other experimental difficulties if we can just use a software-implemented notch filter to erase the power line noise in the data?

In most cases the pickup of power line noise in unshielded experiments is so strong that the 50 Hz or 60 Hz signal starts to saturate the amplifiers. This causes the amplifiers to behave nonlinearly, so instead of a perfect sine wave you see a distorted sine wave. If we look at this distortion in the frequency domain instead of the time domain, we begin to add **harmonics** at integer multiples of the fundamental frequency. The notch filter will remove only the fundamental frequency, not the harmonics. In a 60-Hz country like the United States, we could remove 60 Hz with the notch filter but we may still have significant components at 120 Hz, 180 Hz, 240 Hz, etc. (The Intan RHX data acquisition software has a Spectrogram tool that can be used to find evidence of harmonics in amplifier signals.) If we use the techniques described earlier in this document to reduce noise amplitude then any remaining 50 Hz or 60 Hz signal is more likely to be highly linear with few harmonics, so the notch filter will work more effectively.

Notch filters have a finite bandwidth, so they also attenuate signals within a few Hz of the target frequency. This can distort LFP waveforms in the 40-70 Hz range. Notch filters also have temporal responses that can produce brief "ringing" artifacts in response to abrupt changes in the input waveform. The best solution to noise is to block it before it reaches the amplifier and only use notch filters if absolutely necessary, especially if there are signals of interest at nearby frequencies.

Summary

A step-by-step process for noise reduction is listed here, summarizing the points explained in this Application Note.

1. **Bundle** or **twist** all signal and reference/ground wires closely together to **avoid large open loops** that can pick up AC magnetic fields.
2. **Minimize the length** of the wires between the headstage and electrodes (ideally less than 10 cm). Long wires pick up AC magnetic fields. If possible, use a probe that connects directly to the headstage.
3. Avoid **ground loops**. Ground loops pick up AC magnetic fields.
4. Add a **Faraday cage** tied to an external ground to block electric fields. Do not connect anything inside the Faraday cage to the cage.
5. If you see prominent noise at twice the line frequency, try shielding your probes from **light**. Silicon probes are light sensitive.
6. Enable the **notch filter** in software to remove residual line noise *only if necessary*.