

## Measuring Noisy Signals With Lawson Labs High Resolution Analog-to-Digital Data Acquisition Systems

Lawson Labs Models 201, 202, 301, 302, 401, EMF 2, EMF 6, and EMF 16 all are built around precise, 24-bit Sigma-Delta A/D conversion. These A/D converters are excellent for rejecting periodic noise when configured appropriately. Best performance will be achieved when some care is taken regarding the characteristics of the noise itself, and how they relate to the exact set-up of the A/D converter. The interaction of noise and configuration is not always obvious from the data, but the tools for optimization are not complicated. The relationships are often explained in the frequency domain (think of Fourier plots of response vs frequency), but the frequency domain tends to be non-intuitive for the uninitiated. Here, we will limit ourselves to the time domain, where time is represented on the horizontal axis.

The A/D converters listed above have high input impedance, making them suitable for precise measurement with sensors having high output impedance. Such sensors, by nature, will pick up ambient noise and mix it with the desired signal. Electrochemistry electrodes are high impedance sensors. The discussion below addresses them, as well as other noisy voltage sources.

If you took a 10 Megohm resistor and connected it across an oscilloscope probe, you would have an antenna for looking at ambient noise. Moving the probe around your cell phone, computer, or monitor, you would see what is picked up out of the air. Generally, line frequency dominates, but other frequencies, such as the operating frequency of a nearby switched-mode power converter, would also appear. You could also see the local radio station or police/emergency radio frequencies. You don't need to perform the experiment, because your signal source and input wiring are an antenna, of sorts. The idea is to make your inputs into poor antennas.

You don't need to worry much about radio frequencies, because the converters listed above will reject radio frequencies under all circumstances. Even so, intense radio frequency fields can cause small DC measurement errors if any rectification takes place in the sensors or data system. In that case, shielding is generally the answer. Shielding almost always helps to reduce noise, though not all shielding is equivalent (more on that later). The larger issue is usually line frequency noise, 60 Hz in the US and 50 Hz in Europe. We will start there.

Running in single-channel scanning mode, the converters above can sample at an internal data rate of 1000 samples per second, which is more than fast enough to digitize a 60 Hz signal. The screen shot below shows 150 mV of mixed 60 and 120 Hz noise picked up by many MegOhms of series resistance in the input leads of an EMF 6 measuring a battery voltage. (The other figures included here were also generated by a standard EMF 6 with the free VB graphics software.) This noise pattern is typical of what to expect for line frequency noise where the line is 60 Hz. Only the time scale would change for 50 Hz line frequency.

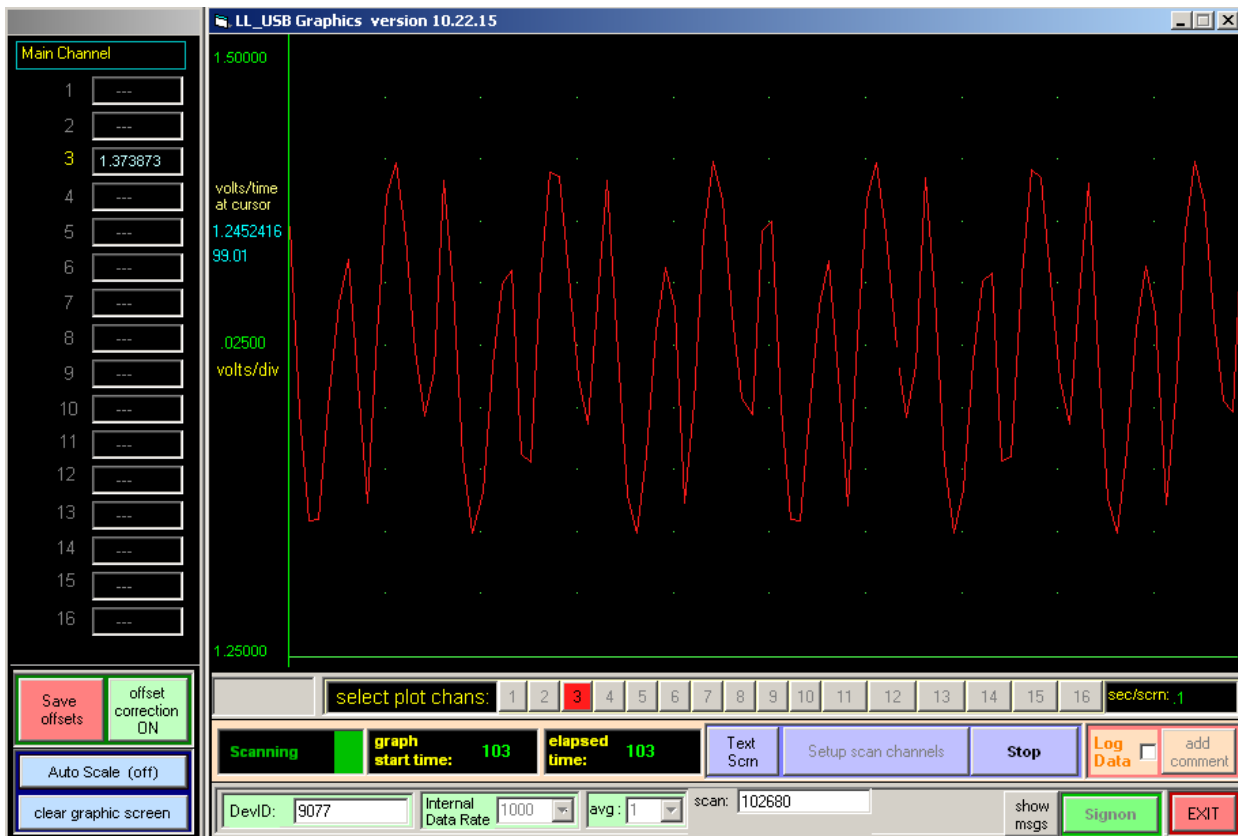


Figure 1

With higher input impedances, it is entirely possible to pick up more than a volt of line frequency noise, which will add to your DC signal. In theory, because the noise is AC in nature, it should not change the average value of your readings. In practice, there are some things to watch for. Since you might want to resolve 10uv buried in 1 volt of noise, you want rejection to 1 part in 100,000, or better. Your A/D system will do most of the work, but you need to help it along.

**A. The first stage of optimization is to minimize the total amount of noise.**

Set your data system up to see the noise while evaluating methods to reduce noise. Later, you will set up to minimize whatever noise remains. Select 1000 samples per second, single channel scanning, with no averaging. Monitor your sensor with the graph scaled vertically to show all of the waveform. For horizontal scaling, 1 second per screen will show individual 50 or 60 Hz cycles, but, 300 or 600 seconds per screen will still show the noise envelope, and will provide a picture over many minutes. That helps because noise and sampling can generate lower frequency interference patterns, called aliasing. Therefore, you need to watch the data over a period of time to be certain you have fully evaluated any particular configuration.

General Grounding Guidelines

Grounding and shielding are the places to look first for reducing noise. All the A/D

systems discussed here are electrically isolated. They all use a separate power supply to energize the isolated circuitry. That means there are multiple points which may be referred to as "ground" which are not necessarily connected together. This can be confusing. The terminology used is not universally consistent, but definitions follow for terms used here and in various Lawson Labs documentation.

**Power ground:** The minus connection on a power supply which provides a positive output voltage

**Earth ground:** A connection to the earth itself, via a grounding rod or water pipe. The third prong on a wall socket should be connected to earth ground, but that is not always the case.

**Chassis ground:** The ground at an electrically conductive enclosure, often connected to the shield on external wiring, such as RS-232 or USB cables. Chassis ground frequently connects to the third prong on a power cord, but not always.

**Guard:** Sometimes used to denote an isolated ground connection

**Common:** A ground which may or may not be isolated from other grounds

**Signal ground:** A connection to power ground that does not carry any significant current so that it can be relied on as a reference voltage of zero volts. (Note that no two ground points can be counted on to be at the exact same potential in any real circuit.)

Ground definitions can be slippery. Some power supplies have an internal connection between power ground and earth ground. Some do not. A laptop computer may, or may not, have its chassis ground connected to earth when running from a charger, but will probably not have an earth connection when running from its battery.

Ground loops are formed when multiple paths to ground are available at a given point (ground connections in parallel). When a ground loop is present, ground currents may take different paths to ground at different times. Because ground currents flow in wires with finite resistance, voltage drops occur, as dictated by Ohm's law (voltage drop = current X resistance). Changes in relative "Ground" potentials can, in turn, cause changes in the paths carrying ground currents. Loads, with associated ground currents can switch in and out. Complex, erratic behavior may result. We avoid ground loops when possible. In general, there should be one, and only one, ground connection for any given point.

For example, you normally do not want the shield of an interconnecting cable to connect to chassis ground at both ends if the connected devices each have their own earth connection. In that case, the cable shield would become part of a ground loop.

Because Lawson Labs A/D systems are isolated, you are never forced into needing to tolerate a ground loop. The flip side of that is you must sometimes ensure that a ground path is provided in order either to meet the operating requirements of the instrumentation, or to improve the effectiveness of shielding.

Because of the isolation, ground at the instrument will be floating with respect to earth ground and the computer's ground unless a path is provided. The EMF models have a switch or jumper to make that ground connection through the minus input wire, but it is best to add a third conductor for what we call the common mode ground. The plus input and minus input connections are ideally for sensing only. No current should flow in those wires. If any ground current is to flow, it should be carried by a separate wire. That way, any voltage drops due to wire resistance will not appear as errors in your readings. You can ignore these small effects with a 16-bit A/D converter, but with A/D resolution to the  $\mu\text{V}$ , a few  $\mu\text{A}$  of current in an ohm of wire resistance becomes a measurable voltage error.

How to add a common mode ground wire:

For electrochemistry, make a relatively low impedance connection between your solution and ground at the A/D system. A second, non-critical reference electrode is fine for the purpose, as long as it has its own separate wire.

For a powered sensor, you would run a separate wire from power ground at the sensor to ground at the A/D system in addition to a wire each for the plus and minus voltage signal. When a separate ground wire is used, use the **DIF** switch position, or otherwise insure that there are not redundant grounds.

Don't cheat. ("But I didn't have an extra wire in my cable.") You might think that connecting point A to point B and point B to point C is equivalent to connecting point A to point B and point A to point C. It is not. Wires have resistance and self-inductance and stray capacitance. They are not ideal conductors. If your results are always fine, don't worry, but if there is room for improvement, the first thing to try is following the rules.

What happens without the common mode ground?

Typically, readings look basically OK, maybe a little noisy, but every so often there is a large spurious spike in the readings. The mechanism is that the spike occurs when the floating input voltage drifts into the upper or lower limit of the A/D common mode range. A protection diode in the A/D system then turns on, drawing a brief current which brings the floating input voltages back into range so that they again read more or less correctly. After a period of seconds or minutes, the process repeats. That pattern is a strong indication of a missing ground.

After checking the grounding, shielding is the next defense against noise.

If there is a chassis ground or metal shield at your sensor, add a wire from it to chassis ground at the A/D system. Remove any other ground connections from the shielding to avoid forming ground loops. The EMF 6 has a brass thumbscrew on the back panel to assist in making a chassis ground connection. You would need to provide the EMF 6 with the connection from chassis to earth. The EMF 16 has a 10-foot grounding cable that works best when connected to earth, because shielding works better when there is a current path to earth ground. A metal water pipe or dedicated ground rod is the best earth ground. The center screw of a wall socket can offer a satisfactory earth ground, but

only if the building's wiring is well done.

A shield does not have to completely surround the sensors and wiring to offer benefits. Sometimes a grounded metal plate nearby will have the desired effect.

Also, it may be more effective to shield a noise source than to shield the A/D input connections. For example, a stirrer may not be plugged into a grounded outlet. Making sure nearby equipment is grounded may improve the noise situation.

Turn equipment on and off while watching your noise levels to identify noise sources. You may need to actually unplug a device to turn it completely off. A computer has a standby power supply that runs even when the computer is "off." We have seen standby supplies which radiate nasty fields, even when the computer is nominally "off."

HVAC systems, heaters, refrigerators, and similar systems will turn on and off on their own schedules. Some equipment runs during the day, but not at night. Lights may be on at night, but not during the day. Interference may come and go along with the operation of certain equipment. HVAC is seasonal. It may take close attention to outside influences that can easily be taken for granted in order to track down a source of intermittent noise.

Other grounding:

Some electrical equipment injects current spikes into the earth ground. A fluorescent lamp with a "start" button can be troublesome when starting. In that case, the earth connection may do more harm than good. Plugging into a separate AC branch circuit (on a different circuit breaker) may help with that category of interference problems.

The fluorescent lamp produces a current spike with fast edges. The AC nature of the disruption means that it does not behave the same way as a DC current. A ground wire may measure at a fraction of an ohm resistance, but if it is 100's of feet long, it has many uHs of self-inductance. A connection of many uHs looks like an open circuit to an AC impulse with a fast edge. Without going into a lot of detail, AC effects are another reason why grounds should be routed as directly as possible, no matter what the ohm meter says.

Many of these systems use BNC connectors for inputs. The outside connection on the BNC connectors will be different for different products and can be customized in many cases. For the standard EMF 16, the outsides go to chassis ground. For the 8-channel differential EMF 16, the 8 signal input BNCs have the minus input there. For the EMF 6, all go to power ground unless the differential channel 6 option was selected, in which case that one BNC has the minus 6 input connection there. The EMF 2 has differential inputs with jumpers to replicate the **SAFE** switch position of the EMF 6 and 16. Check the block diagram to be sure.

Regardless of whether you start with "best practices", or what's most convenient, you can experiment to optimize grounding. What ever works the best is OK.

Differential input balance:

These A/D systems all have true differential inputs with excellent "common mode rejection." That means the A/D systems respond to the difference between the plus and minus input terminals, not to the absolute voltages. Still, the absolute voltages must be within an acceptable range (usually +/-6 volts for Lawson Labs products) for proper operation. If the plus and minus inputs are connected together and are connected to a signal source that imparts a voltage in reference to ground, the differential input voltage remains at zero, so the reading should, too. To the extent that there is any imbalance between the two inputs, readings may reflect a small amount of the common mode signal. The higher the frequency of the common mode signal, the more important that balance becomes. Unmatched inductance, resistance and capacitance can cause phase shift between the plus and minus inputs, which would show up as a differential voltage error. The more symmetry in the input wiring, the better, both electrically and geometrically.

Positioning:

Radiated noise is directional. Simply rotating the apparatus may increase or decrease noise pickup. More physical separation between noise sources and sensitive points will improve your signal.

Be aware of intermittent noise sources, including HVAC, emergency radio traffic, motors, including stirrers and pumps, non-incandescent lighting, etc. Your movements in the vicinity of your sensors modulate interference fields, making your data system behave like a motion detector.

Your input connections form a loop, and any loop acts as an antenna. The amplitude and frequency of the signals picked up by the loop depend on the loop geometry. It will always be better to reduce the loop area, which is the area outlined by the physical wiring. Minimizing loop area is the logic behind twisted pair signal wiring and Romex-style AC power wiring.

## **B. The second stage, reject the remaining noise**

After you minimize the amount of noise picked up by your sensors and wiring, the next stage is to maximize the noise rejection of your A/D system for the remaining interference.

Pick the right data rate and averaging:

Now, set the internal data rate to the line frequency, or to the frequency of the preponderant noise, if some other frequency. For single channel scanning, a combination of data rate and averaging will accomplish the same purpose. For example, instead of a data rate of 60Hz, a rate of 120 Hz with averaging set to two will yield similar results. In multi-channel scanning, the phase relations get more complex, so less can be gained by using faster rates and digital averaging. In other words, for multi-channel scanning it is rare that you would not use the line frequency, or an integer division of line frequency, as your internal data rate.

Figures 2 and 3 show the before and after for picking a correct internal data rate and averaging combination. The importance cannot be overemphasized.

Aliasing is the appearance of spurious lower frequencies due to phase interactions of the sampling system and the noise. In Figure 2 the rate is 120 Hz and the averaging is 1. The noise is the same combination of 60 and 120 Hz components seen in Figure 1. Figure 2 shows 5 minutes of data. The non-intuitive pattern of low frequency aliasing can be clearly seen. Vertical scaling is 3 mV per division. Your A/D system can do a lot better than this.

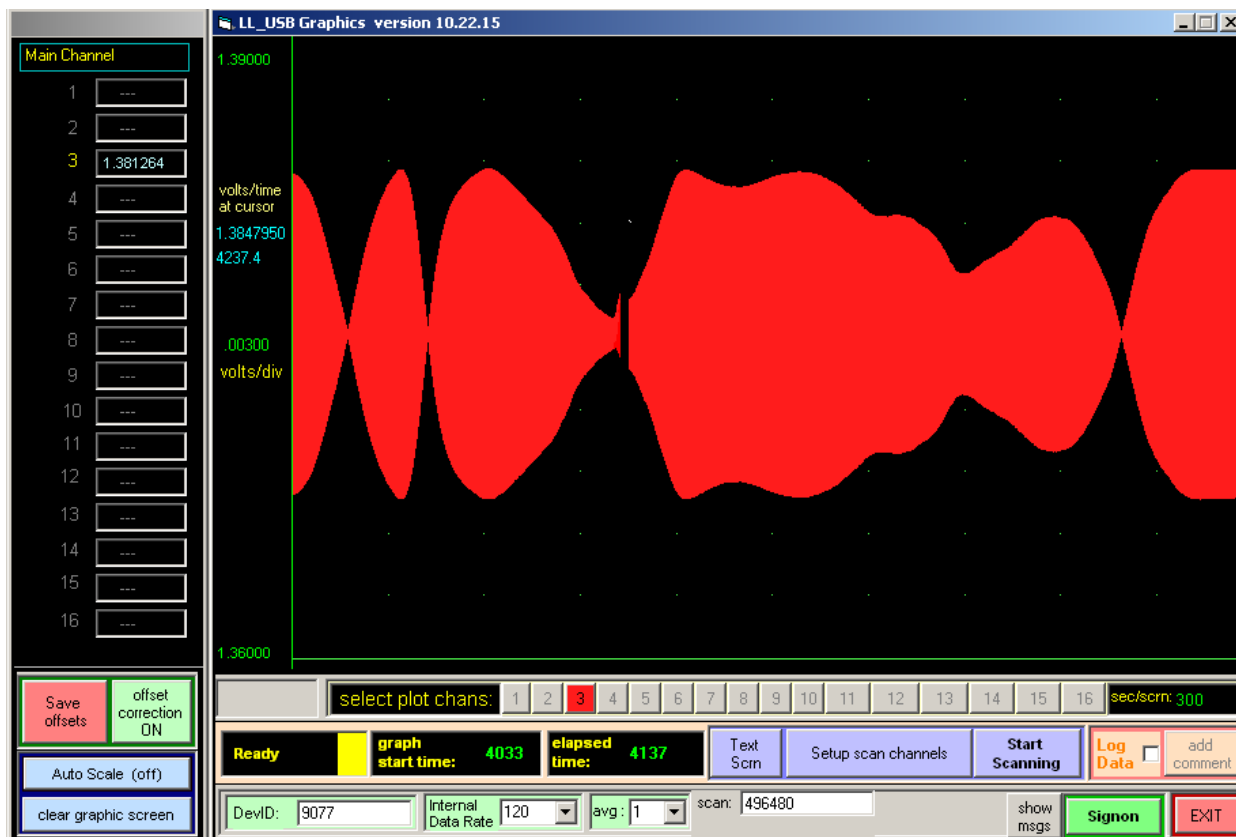


Figure 2

With averaging set to 2 at a 120 Hz internal data rate, both 60 and 120 Hz components are rejected. Figure 3 shows the same signal acquired with everything the same except the average setting. Note that the vertical scaling is now 100 uV per division, instead of 3 mV, and that any 60 or 120 Hz interference vanishes into the +/-10 uV of background noise.

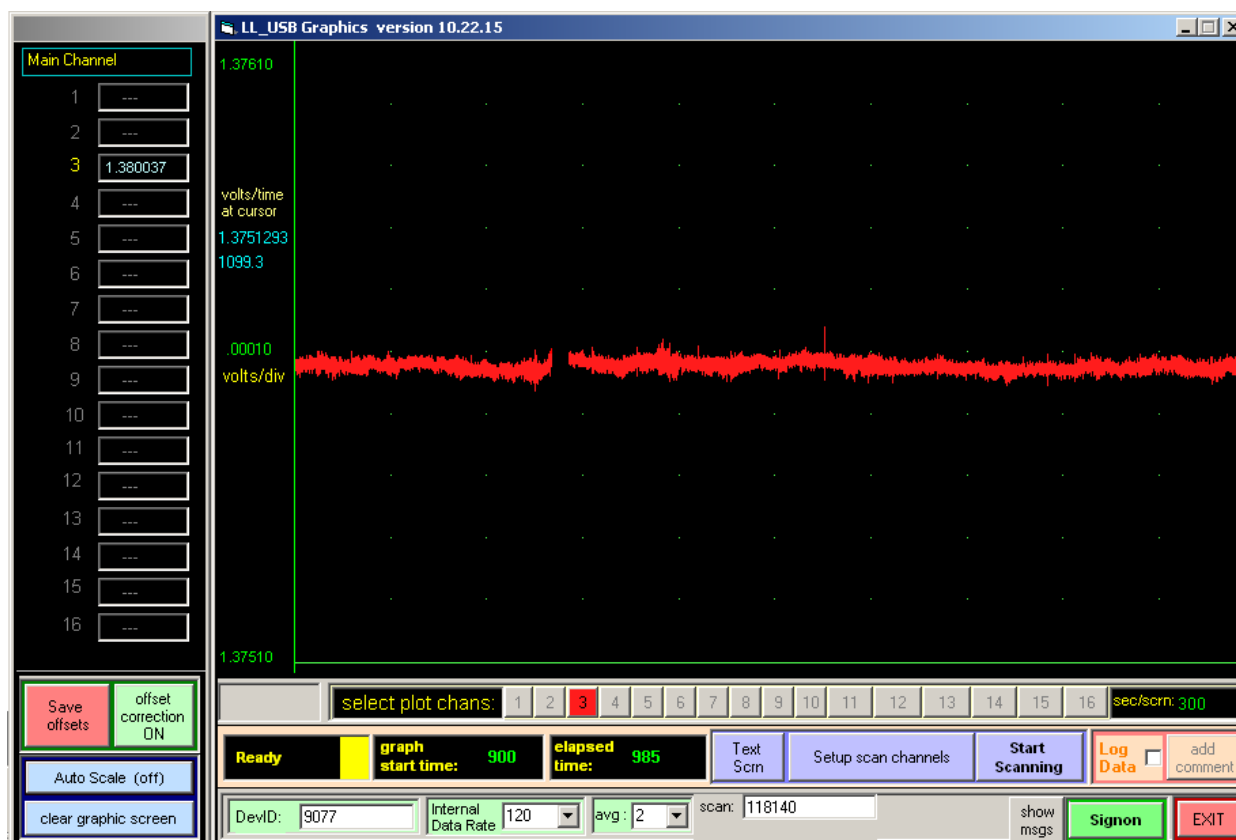


Figure 3

Power grid line frequency is correct on the average, but may drift around a little over a period of hours. As that frequency wanders, you may see a little more or less aliased low frequency noise. One solution for eliminating this artifact is a physical filter on each input to reduce the amplitude of interference. For electrochemistry, a film capacitor of 0.01 uf from an input to ground will remove line frequency noise, but will also slow the response to a step change. A value of 0.001 uf may offer a better compromise, depending on the impedance of your electrodes. Simply increasing the averaging factor may provide enough stability, and with faster settling.

Note that quite a few things must be carefully addressed in order for a noisy signal to be digitally cleaned to the extent shown in Figure 3, and to still result in an accurate DC reading. Numbers 3, 4 & 5 are taken care of for you in our A/D systems, but they apply to your sensors and signal conditioners (if any).

- 1) You need to average an integer number of noise cycles (as explained above)
- 2) You need to stay away from the extremes of the input range. A 4.1 volt signal with 1 volt of noise riding on it will hit the 5 volt stop during each cycle, destroying the DC accuracy.
- 3) Your A/D converter needs to have excellent linearity so that the averaged readings



over a range actually match the average value of the voltage.

4) Slew rate for positive- and negative-going signals must match.

5) There should not be any rectification of AC signals occurring anywhere in the data system. Rectification translates AC interference into DC errors.

Figure 4 shows an optimized system, still with over 150 mv of noise riding on the input. Here, the internal data rate is 60Hz, which is optimal. We also are performing a running average of 4 data points for each displayed point. The running average of 4 reduces the noise approximately in half and adds only 1/15th of a second to the settling time.

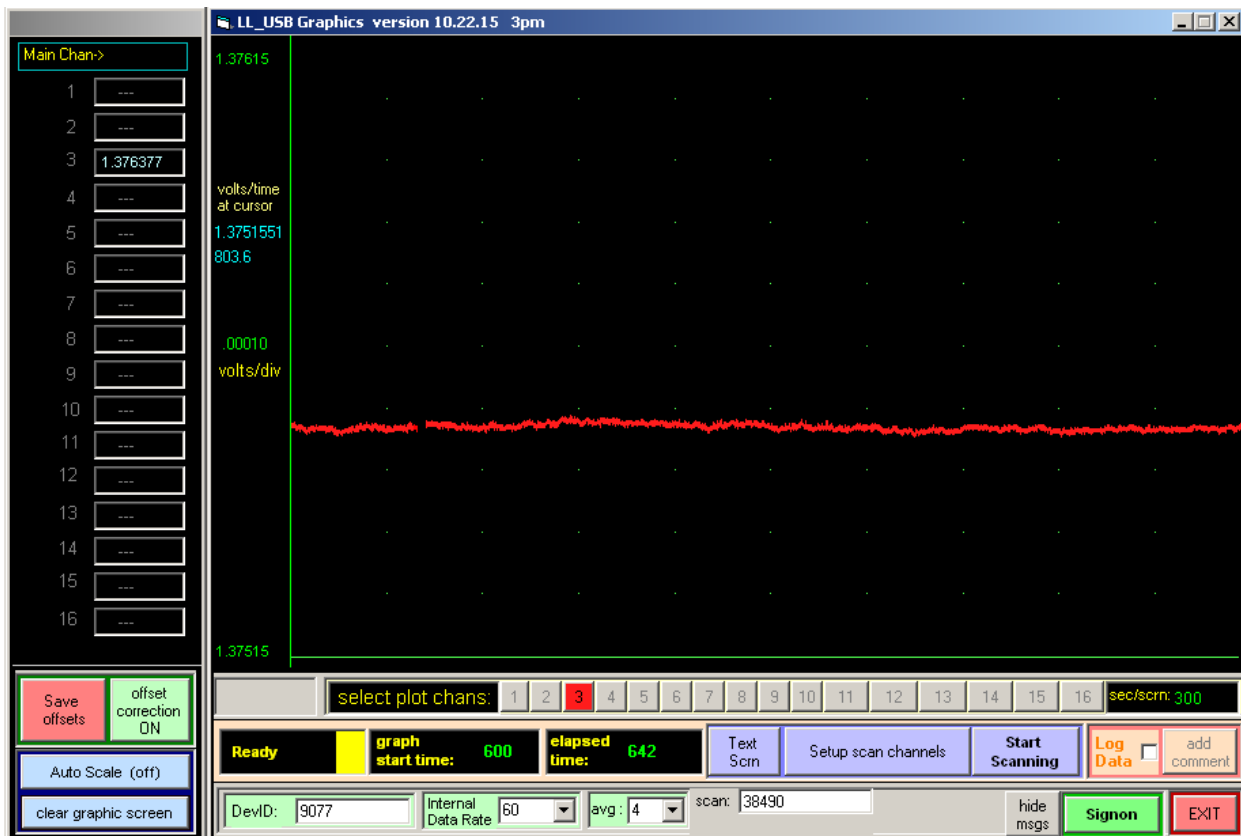


Figure 4

## Conclusion

Once you have the noise well under control, add any additional data channels to your scanning set-up. Yes, that will reduce the scanning rate, but it will provide the cleanest data. If you speed up the internal data rate to compensate, you will again increase the amount of noise seen. You can always increase the running average to suppress noise, but remember that averaging has the effect of reducing your time resolution.

The USB and TCP/IP interfaced A/D systems are about 20 times faster than their RS-232 equivalents. We recommend those systems for best time resolution. Simply

averaging noisy data won't produce excellent DC results unless your A/D converter has the linearity, stability and DC accuracy to begin with. 24-bit Sigma Delta converters with full DC specs (like Lawson Labs products) are the best choice for these applications.

Contact the factory if you cannot achieve the level of resolution and accuracy that you desire. We can almost certainly help.