

Considerations for Analog Input and Output

Useful information can be found in the text in Sections 6.7.1 (Data Rates), 6.7.5 (Analog Input Signals), 6.7.6 (Multiple Signal Sources: Data Loggers), 6.7.9 (Personal Computer Control of Experiments), and 6.9 (GROUND AND GROUNDING).

1.0 Input Connections

The data acquisition equipment we use in Physics 240 in C460 ESC is the National Instruments USB-6221-BNC, which is an M-Series device. The equipment used in Physics 245 in C435 ESC is the National Instruments PCI-6040E or PCI-MIO-16E-4, which is an E-Series device. For more information on the connections in these devices you should see either page 4-12 of the [DAQ M-series manual \(http://www.ni.com/pdf/manuals/3710221.pdf\)](http://www.ni.com/pdf/manuals/3710221.pdf) or page 2-21 of the [DAQ E-series manual \(http://www.ni.com/pdf/manuals/370503k.pdf\)](http://www.ni.com/pdf/manuals/370503k.pdf).

Links to both manuals are available on Learning Suite in either **Content** ⇒ **LabVIEW Basics Course** ⇒ **Effective Analog Input and Output** or **Content** ⇒ **Manuals for Equipment Used in Physics 240** or on the class web page.

The connections for our analog input devices are configured to be used only in the differential mode. This means that they will measure the voltage difference between the two leads of an input connection but does not assume that either of those leads is at ground potential. This is beneficial for two reasons.

1. It doesn't matter if the ground reference of the external circuit is different from the ground for the analog input device as long as the difference is sufficiently small.
2. If there is a noise voltage picked up by the leads, it will not be included in the measurement as long as both leads pick up the same noise. The use of either a shielded cable such as coaxial cable or twisted pair wires will increase the likelihood that both leads will pick up the same noise, so it will not be included in the measurement with a differential device.

1.1 Grounds

Note: If you haven't read Section 6.9 in the text you should do so. It expands on and is complementary to the following information.

In electronic and electrical circuits, the concept of a "ground" is very important. In electrical power distribution circuits, the ground is required for safety as a path for "errant" current to follow rather than through the user.

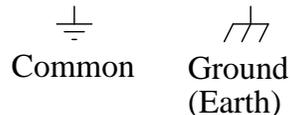
Ground, as used in the code for electrical wiring, is a reference to a direct connection to a conducting stake driven into the ground somewhere nearby. The AC power distribution system is designed to use the earth as part of the return current path to the generating stations.

The ground connection for individual devices is usually provided by the power distribution ground connections. In some cases, a local dedicated ground connection may be provided for specific equipment or a particular laboratory. This is especially true for equipment that deals with high-frequency signals. In those cases, a very low-inductance ground is necessary for reliable operation.

1.1.1 Ground or Common?

In electronic circuits, the term “ground” often refers to the “common” portion of a circuit and not necessarily to that point connected to an earth ground. The common terminal usually serves as a reference point from which most voltages are measured since voltage only has meaning when given with respect to some known reference point. This reference point may be but is not necessarily connected to the “earth ground.”

The common for a circuit is represented in most circuit diagrams by the symbol on the left, and the earth ground is represented by the symbol on the right.



The analog interface devices we use will typically have two to four grounds specified. They can include analog input ground (AI GND), analog output ground (AO GND), digital ground (D GND), and chassis ground (CHS GND). These grounds are not guaranteed to be equal in voltage. The first three are *common* terminals for the specified sections of the interface device. Chassis ground is the true or earth ground (connected to a stake in the ground through the AC power distribution system) described above – assuming that your device is properly grounded to the distribution system.

These grounds are explicitly separated in the analog interface board to avoid interactions between the digital and analog sections of the devices. It is good practice to keep your analog and digital grounds separate if possible.

1.2 Ground loops

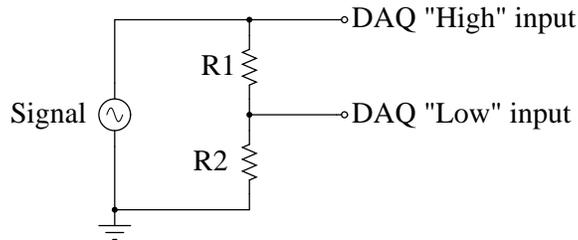
If you have a ground connection both on the source of the signal and on the analog input device, you create what is called a ground loop. That is, you have a wire that connects your signal source to the analog input device as well as a parallel connection between the grounds. This parallel connection will usually involve the building electrical ground system. These parallel wires create a potentially very large loop (also known as an antenna) that serves to introduce noise signals on your input. Under some conditions, these noise signals can get very large.

You want to ensure that you have *only one ground connection* in your circuits. ***A much too common exercise in experimental measurements is looking for ground loops to reduce noise signals.***

1.2.1 Analog input configuration

When you use these devices, you will need to determine whether to use the “grounded source” (GS) or the “floating source” (FS) configuration for analog inputs.

Keep in mind that “grounded source” can mean either that one side of the signal is grounded or that it is held at a particular voltage with respect to ground. For example, for this circuit



you should select the **GS** configuration, or you will modify the effective value of R2 by the presence of the grounding resistor provided by the analog input device. In the devices we use, a resistance of $5\text{ k}\Omega$ is connected from the “low” or “-” input to AI GND in the FS configuration.

2.0 Signal conditioning

Most sensors require some form of signal conditioning before the value is compatible with the DAQ input. The National Instruments document “[The Engineer’s Guide to Signal Conditioning](http://www.ni.com/engineers-guide-)” (<http://www.ni.com/engineers-guide->

to-signal-conditioning) provides useful information regarding signal conditioning. (Note: you will be asked to create a free account on the web site before you can download the document. You can find the document at http://download.ni.com/evaluation/signal_conditioning/20712_Benefits_of_Integrated_SC_WP_HL.pdf without creating an account.)

Another document that you may find useful is Measurement Computing's "Data Acquisition Handbook, 3rd Edition" found at <https://www.mccdaq.com/support/Data-Acquisition-Handbook.aspx>. It has extensive information on data acquisition and signal conditioning.

Appropriate signal conditioning can make the difference between a marginally useful measurement and an accurate measurement.

3.0 Device specifications

The device specifications for both the devices we typically use are available at <http://www.ni.com/pdf/manuals/375201c.pdf> for the USB-6221-BNC and <http://www.ni.com/pdf/manuals/370722c.pdf> for the PCI-6040E/PCI-MIO-16E-4. Links to both these documents are available on Learning Suite in either Content \Rightarrow LabVIEW Basics Course \Rightarrow Effective Analog Input and Output or Content \Rightarrow Manuals for Equipment Used in Physics 240 and on the class web page.

When you are deciding if a device will work for your application, there are several particular specifications you need to consider.

3.1 Overvoltage protection

Note the values given for the "overvoltage protection." If you exceed these values, you will likely cause expensive damage to the device. For both devices, this is ± 25 V if they are powered on and ± 15 V if powered off. ***To be safe, always keep the input voltages within ± 15 V of ground.***

3.2 Maximum working voltage

For both devices, the "maximum working voltage" is specified as ± 11 V measured with respect to the analog input ground. This means that the combination of all the voltages applied to an input (both the "high" and "low" inputs) must not exceed ± 11 V from analog input ground. If you exceed that voltage range, the device will give very unpredictable – and wrong – results. One of the common causes of exceeding the ± 11 V limit is having no ground reference in a circuit so that it can drift

uncontrollably. This is an especially important consideration if you have the device set to the **GS** configuration.

3.3 Device resolution

The number of bits used to specify a number for a given device will be specified in the documentation. This value indicates the number of discrete levels into which the input voltage range will be divided. The number of levels will be given by 2^b where b is the specified number of bits. For instance, a 12-bit device will use $2^{12} = 4096$ levels to represent the input signal. A 16-bit device will use $2^{16} = 65536$ levels.

The number of bits is combined with the available input range(s) to determine the device resolution in terms of volts/level. This is referred to as the “Code Width” in Chapter 7 of the LabVIEW Basics 1 Course. For comparison, the resolutions at the various input ranges for our two devices are listed in [Table 1](#). Input ranges for which there is no code width entry are not available for the specified device. The code width, or minimum resolvable voltage change, is given by the total input voltage range ($V_{max}-V_{min}$) divided by the number of levels minus 1 (2^N-1 where N is the number of bits in the input converter).

For most devices, there are specific input ranges available due to hardware limitations. The software will usually select the input range with limits greater than or equal to the requested range. For instance, if you request a range of -1 V to $+3\text{ V}$, the USB-6221 will be set to a range of $\pm 5\text{ V}$ since your requested range will not fit entirely in the next available range of $\pm 1\text{ V}$.

To get the best results you want to specify the input range to be as close to the expected range of your signal as possible. This will result in the smallest possible code width.

3.4 Input impedance

The PCI-6040E has an input resistance of $100\text{ G}\Omega$ in parallel with 100 pF . The USB-6221 has an input resistance of $10\text{ G}\Omega$ in parallel with 100 pF . The input resistance of both devices is sufficiently large that the analog input will have a negligible effect on the circuit in most cases.

The capacitance in parallel with the input resistance can cause problems at high frequencies. For instance, at 100 kHz the reactance of that capacitor is about $16\text{ k}\Omega$ – a value that can be important in many cases.

Table 1: Code widths for the available input ranges for the PCI-6040E (12-bit) and USB-6221 (16-bit) devices. The design of the USB-6221 makes the code width about 5% greater than the specified values. For instance at an input range of ± 1 V, the standard formula would give $30.52 \mu\text{V}$ while the actual code width was about $32.45 \mu\text{V}$ for one device that was tested. Input ranges for which there is no code width entry are not available for the specific device.

Input Range	Code Width	
	PCI-6040E (12-bit)	USB-6221 (16-bit)
± 10 V	4.9 mV	305 μV
0 – 10 V	2.44 mV	
± 5 V	2.44 mV	153 μV
0 – 5 V or ± 2.5 V	1.22 mV	
0 – 2 V	488 μV	
± 1 V	488 μV	31 μV
0 – 1 V or ± 0.5 V	244 μV	
0 – 0.5 V or ± 0.25 V	122 μV	
± 0.2 V		6 μV
0 – 0.2 V or ± 0.1 V	49 μV	
0 – 0.1 V or ± 0.05 V	24 μV	

3.5 Sample rate and aliasing

The “maximum sampling rate” indicates the fastest acquisition rate you can use with the device. For the PCI-6040E this is specified as 500 kS/s (kilosamples/sec) for a single channel and 250 kS/s for multiple channels.

For the USB-6221 it is given as 250 kS/s for a single channel and 250 kS/s “multichannel aggregate” when acquiring multiple channels. This means that the A/D converter and input switching electronics can only handle 250 kS/s overall. If you are acquiring four channels, the fastest you can acquire each channel is $250/4 = 62.5$ kS/s.

The sample rate is important for deciding if you can accurately acquire the signals in which you are interested. Chapter 7 in the LabVIEW Basics 1 Course manual discusses the *Nyquist frequency*. This is the *minimum sample rate* you need to detect the presence of a particular frequency and is *given by twice the highest frequency component of the signal*. Sampling below this frequency can result in some very interesting – and wrong – results.

It is also necessary to consider signals that are present but may not be of interest.

For instance, if you are sampling a 10 kHz signal, you may select a sample rate of 30 kS/s. However, if there is a 50 kHz signal present this sample rate will alias the higher frequency signal to 10 kHz and it will contaminate the signal in which you are interested. You need to be cautious when selecting a sample rate to avoid aliasing in the results.

If you wish to record an AC signal with a frequency of 10 kHz, you will need a sample rate of *AT LEAST* 20 kS/s. This sample rate will only give two samples/cycle – which does not provide a good picture of the signal other than indicating the presence of some component at that frequency. You would probably want to have four or more samples/cycle (a sample rate greater than 40 kS/s for this example) to get a reasonable representation of the signal.

For some examples of the effect of sampling rate on the recorded signal, see Figures 1 and 2.

3.6 Settling time

If you are taking data from multiple channels, you also need to be concerned whether there is adequate time after the input multiplexer switches for the voltage to settle properly. This is partially due to the input capacitance of the amplifier following the multiplexer and the output impedance of the device providing the signal to be recorded. It is also a function of the quality of the input amplifier and how fast it can settle after an abrupt jump in the input voltage.

The input amplifier that National Instruments uses in most of their analog input boards is very good with a settling time of a few microseconds.

Minimize the effects of the external circuit if possible. For example, if the external circuit has an output impedance of 5 k Ω and you consult the chart for settling time on page 2 of the specifications for the USB-6221-BNC, you will find that the expected settling time is about 20 μ s.

If you are acquiring several channels with a USB-6221-BNC, the default time between sampling successive channels is 14 μ s as long as the aggregate sampling rate is less than 72 kS/s. This time comes from the shortest sample interval the device is capable of, 1/250 kS/s = 4 μ s, plus 10 μ s according to the documentation for the DAQ Assistant VI in LabVIEW.

The interchannel sampling time is less than the settling time found in the previous paragraph. It may not be possible to get the desired accuracy with the default delay unless the output impedance of the source is reduced.

An alternate method of getting the desired accuracy would be to sample the same channel several times in a row, effectively increasing the available settling time, and

keeping only the final reading as the correct one.

4.0 Analog output

Both devices are capable of 2 independent channels of analog output. The PCI-6040E uses a 12-bit digital-to-analog (D/A) converter with an output range of either ± 10 V or 0-10 V. These give a minimum voltage increment (similar to the Code Width on an analog input) of 4.88 mV or 2.44 mV respectively.

The USB-6221 uses a 16-bit D/A converter with an output range of ± 10 V and a minimum voltage increment of $305 \mu\text{V}$.

The PCI-6040E has a maximum update rate of 1 MS/s and the USB-6221 has a maximum rate of 833 kS/s. Most applications of the analog outputs will not be able to achieve the maximum update rate.

For both devices, the maximum current available from each analog output is 5 mA. This is a very low current. It is often necessary to use an op-amp or a transistor on the output to provide adequate current for the device being driven. If your external circuit draws more than 5 mA from the analog output your output voltage will be incorrect.

5.0 Input offset voltage

Because of the imperfections in analog electronics, you will find that your analog input device has a small input offset voltage. That is, if you short across the input to get a 0 V signal you will record some small non-zero voltage with the input device. This voltage may drift from day to day due to electronic and environmental conditions.

It is not unusual for the offset to drift significantly as a device warms up after being turned on. For most devices, after turning them on you will want to wait about 15 minutes for them to stabilize. Once the device is up to operating temperature, it is usually very stable for periods of at least several hours.

If you are concerned about the absolute value of your measurements, you should always measure the offset voltage and subtract it from your signal to ensure that the recorded values are correctly measured with respect to the ground in your circuit.

6.0 Dithering

Dithering is a technique for improving the resolution of a measurement. Some analog input devices will provide the capability for hardware dithering that can be enabled. Dithering is done by adding a small, random voltage to the signal at the input of the analog-digital converter and averaging the measured values over a sufficiently long period to remove that added random signal. This is frequently used for high-resolution measurements when the signal of interest is slowly varying.

Both the USB-6221 and the PCI-6040E are capable of dithering but enabling that feature requires some relatively advanced LabVIEW programming. It is not possible to enable dithering with the DAQ Assistant input VI.

7.0 Electrical noise

Noise on an electrical signal is unavoidable. There are many sources of noise, but most of them result in a random voltage signal. If you are involved in measuring low-level signals, you will spend considerable time removing noise from those signals.

One method of removing noise is to average over many samples if the signal of interest is slowly varying. This will remove some portion of the noise signals because of their random nature.

Another method of reducing noise signal levels is to filter your input signal. Depending on the nature of your signal and that of the noise, you may choose a high-pass filter, a low-pass filter, a band-pass filter, or a notch filter.

Low-level random noise may be beneficial in some circumstances because it serves almost the same purpose as dithering by providing a random shift in the signal. If you acquire many samples and average them, the random noise signal will average to zero and you will be left with the actual value of the desired signal. This will often result in a value that is not exactly at one of the standard code levels and you have effectively increased the resolution of the device.

For more information on noise in signals see the handout on [“Uncertainty, Errors, and Noise in Experimental Measurements”](#) or on Learning Suite in [Content](#) ⇒ [LabVIEW Basics Course](#) ⇒ [Uncertainty, Errors, and Noise in Experimental Measurements](#) or the class web page.

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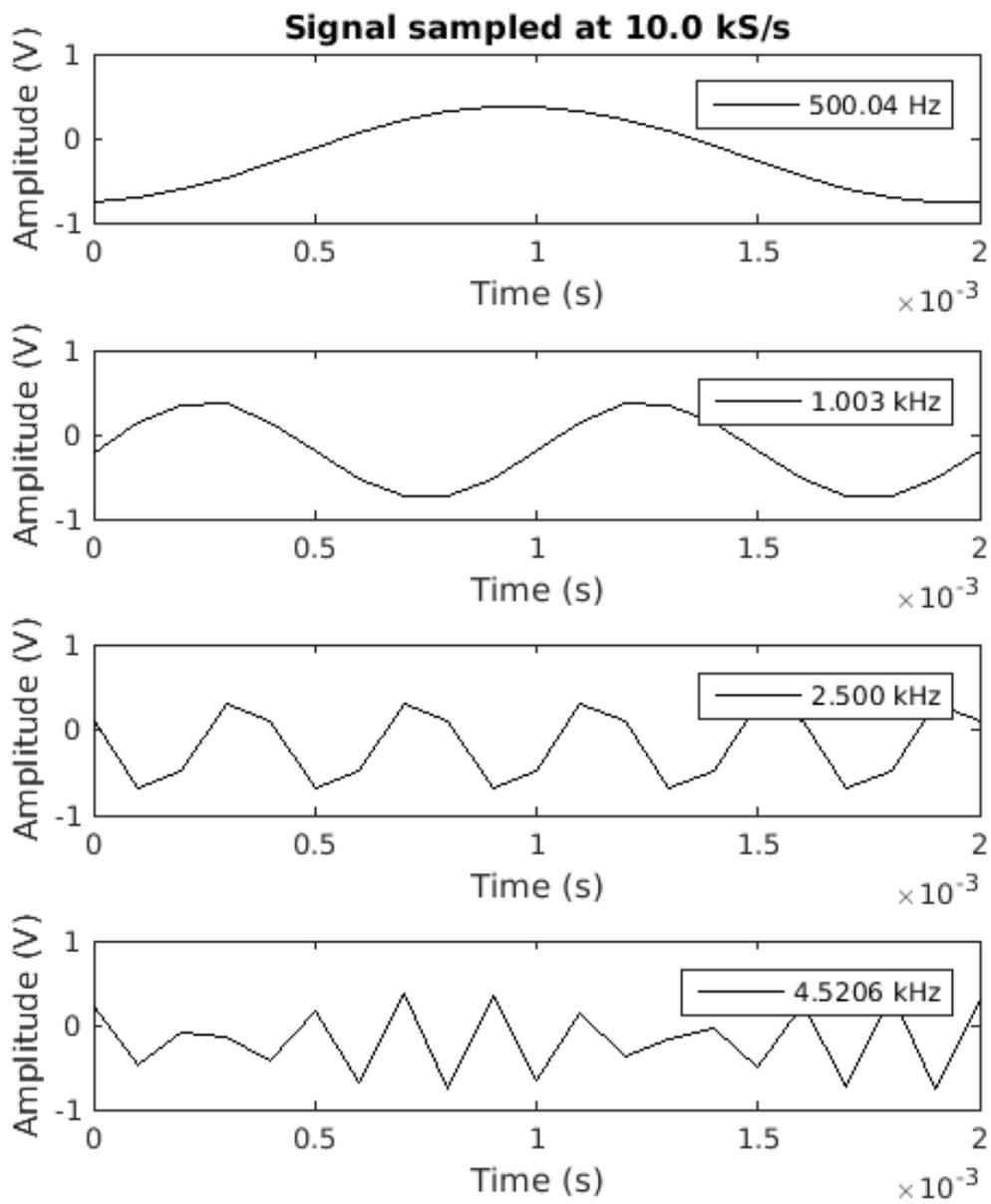


Figure 1: Result of sampling various frequency sine waves at 10 kilosamples/s

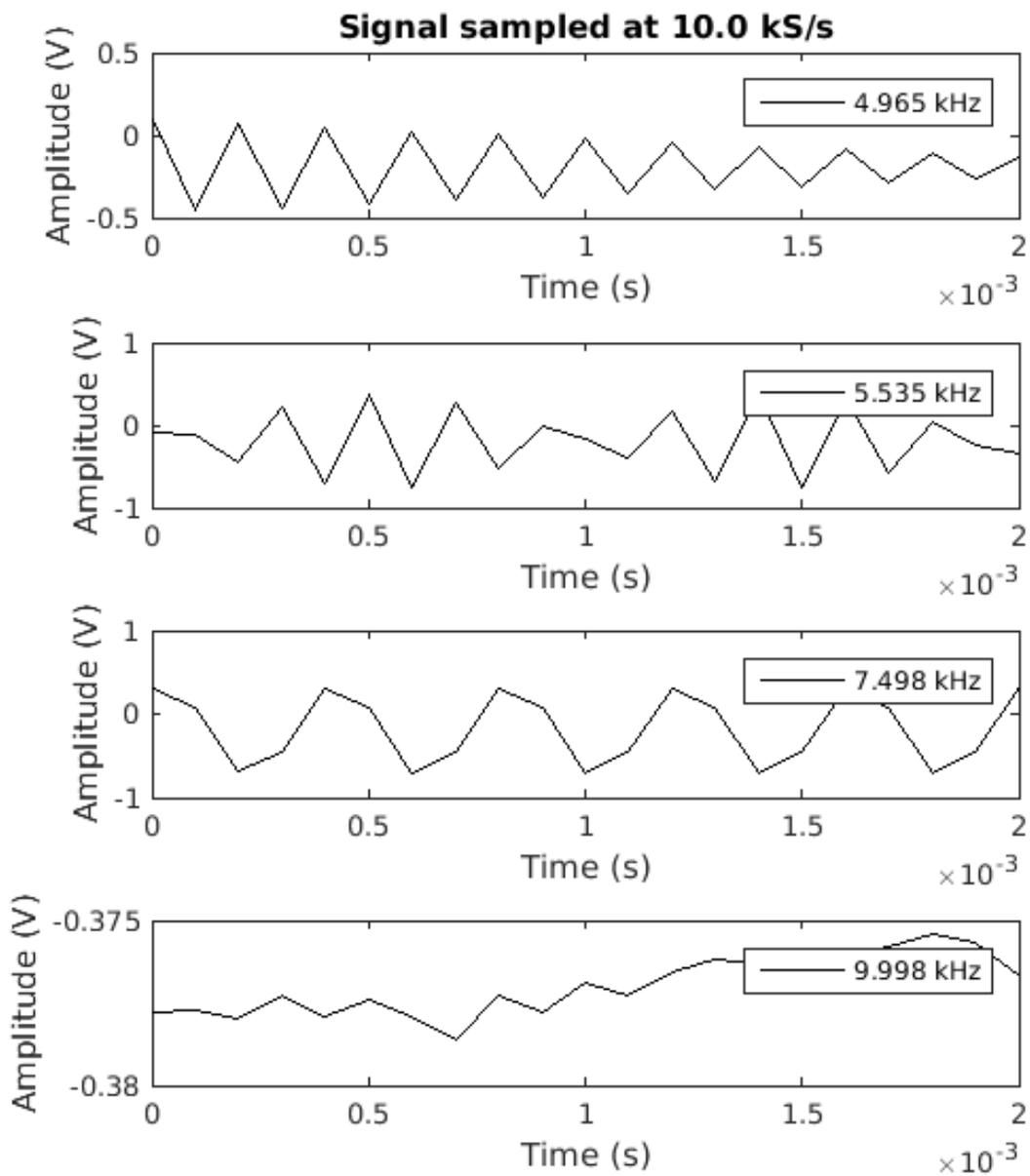


Figure 2: Result of sampling various frequency sine waves at 10 kilosamples/s