FAQ – General
How do I select the most appropriate E and I Filters?

Subject: Instrument Properties – E & I Filters

Introduction

In the broad field of electrochemistry, potentiostats are used to measure batteries, sensors, and corrosion cells, among other cell varieties. These cells may respond quickly or slowly and generate high or low currents, sometimes both in a single experiment.

Princeton Applied Research potentiostats are designed with flexibility to tailor their function to specific applications and cells. These options are selectable within the *Advanced Panel* of VersaStudio under *Instrument Properties*, as shown in **Figure 1**. This note addresses the E and I Filters and is part of a series intended to educate users on the function of the various *Instrument Properties* so that the best measurement can be acquired.
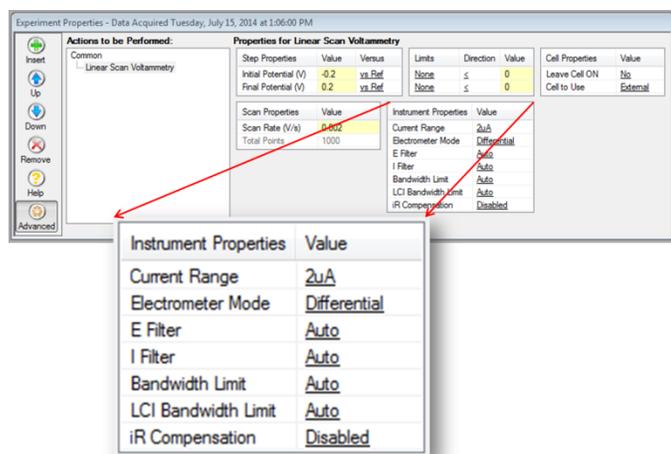

Figure 1: *Experiment Properties* window in VersaStudio showing the *Advanced* panel where the *Instrument Properties* settings can be selected.

Environmental electrical noise is present in any laboratory. The source of this noise ranges from nearby equipment and instrumentation to HVAC systems and lighting. The quality of experimental data collected by various laboratory instruments, including Princeton Applied Research potentiostats, can be impacted by this environmental noise. Fortunately there are a variety of methods to reduce this impact; these include using a Faraday Cage (see "Noise Mitigation Using a Faraday Cage" at www.princetonappliedresearch.com), reducing environmental noise at the source (i.e. powering off nearby equipment), application of data smoothing techniques or hardware filters, among others.

Hardware Filters

All Princeton Applied Research potentiostats contain hardware filters, specifically low pass filters, designed to remove noise from the analog signal prior to converting it to a digital signal (via the ADC). These filters do not affect the speed at which the requested potentiostatic or galvanostatic stimuli are applied to the cell. The low pass filters are applied outside the voltage and current application circuits and before the analog to digital converters used to measure the voltage and current. They can mitigate environmental noise and noise arising in the cell itself.

Filter Basics

A low pass filter's function is to pass signals with frequencies below the filter's cutoff or corner frequency (f_c), while greatly attenuating signals with frequencies above this value.

In VersaStudio, these filters are designated by their -3 dB cutoff frequency, meaning that a 200 kHz E or I Filter

will greatly attenuate signals with frequencies above 200 kHz.

The available filters depend on the potentiostat model. For example, the VersaSTAT 3F has the following filters: 200 kHz, 1 kHz, 100, 10 and 1 Hz filters. The 1 Hz filter will filter more of the signal than the 200 kHz filter.

The measured E and I signal is filtered, if selected, by a first-order linear circuit that attenuates rapid changes in the signal. As a result, the output of the filter, and hence the digitized data presented to the researcher, can only change so fast, even if an instantaneous change occurs at the cell. This output change can be characterized by its rise time, which is the time the signal takes to change from 10% to 90% of its final value. This time is directly correlated to the filter corner frequency by:

$$t_r \approx .35 / f_c \quad \textbf{Eq. 1}$$

for first-order linear systems (as is the case for the E and I filters).

For example, suppose that an E or I signal from the cell is filtered by the 200 kHz filter and changes between two voltage or current levels almost instantly. Instead of an instantaneous change being applied to the ADC and digitized and seen by the researcher, the change will occur over

$$t_r \approx \frac{.35}{200\ kHz} = 1.76\ \mu s$$

as the signal rises from one level to the final level. Therefore, if the researcher is interested in signals changing slower than 1.76 us, the 200 kHz filter will smooth the data and unwanted noise above 200 kHz will be reduced significantly.

The E and I filters may be used to block unwanted noise but must also be chosen to allow frequencies and rise times of interest to pass. Determine the fastest rise time that is needed to be observed and use **Equation 1** to find the f_c. Select the filter that is nearest but still greater than this f_c value. This setting will reject the maximum amount of noise while still allowing frequencies of interest to be observed.

The sampling rate, defined in VersaStudio by the time per point, must also be chosen correctly. If the researcher is interested in rise times of 10 us, for example, then the time per point should be set at 10 μs

or less in order to observe the transition between signal levels. If set to less than 10 μs, more data points will be observed in the transition region making the transition more evident; however, this comes at the expense of more data collected and processed. **Table 1** correlates these aspects.

Fastest Rise Time of Interest	Suggested Filter Setting (if desired)	Maximum Time per Point
< 1.75 μs	Do not use filter	< 1.75 μs
1.75 μs	200 kHz	1.75 μs
350 μs	1 kHz	350 μs
3.5 ms	100 Hz	3.5 ms
35 ms	10 Hz	35 ms
350 ms	1 Hz	350 ms

Table 1: Correlation between signal rise time, filter setting, and sampling rate for the VersaSTAT 3F.

Examples

Filters are especially useful when making low-current measurements, as is the case when using microelectrdoes. **Figure 3** shows the impact of different levels of filtering on data collected at a Pt microelectrode (25 μm diameter). These cyclic voltammograms (CVs) were collected using a PARSTAT MC 1000 (PMC-1000), a Pt counter electrode and Ag/AgCl reference electrode in a solution of 1 mM $K_3[Fe(CN)_6]$ in 0.1 M KCl. The blue CV was collected with the E and I Filters set to "none", while the red and black CVs employed the 10 and 1 Hz filters, respectively.
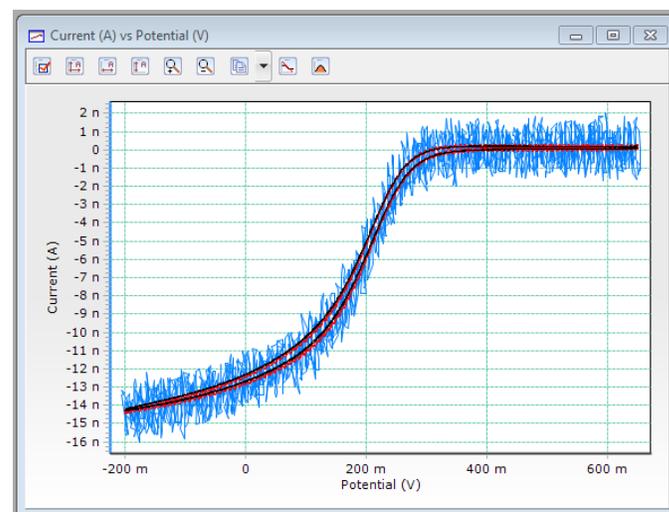

Figure 3: CVs of a Pt microelectrode without (blue), with 10 Hz (red) and with 1 Hz (black) E and I Filters. Scan rate = 10 mV/s.
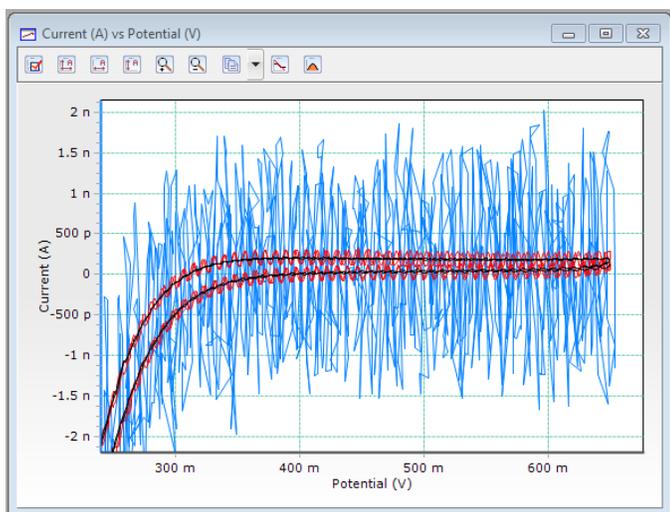
Figure 4: Close-up view of the CVs presented in Figure 3.

From **Figure 3**, it is clear that applying the 10 Hz filter to the E and I channels (red) generated much smoother data as compared to not using any filters at all (blue). **Figure 4** provides a closer view of the same data, making it apparent that the 1 Hz filters produces even smoother data.

The effect of filter selection and sampling rate is illustrated in **Figure 5** by comparing the blue (no filter) and the red (1 Hz filter) data series. In this experiment, the potential is pulsed from +1 to -1 V across an AC dummy cell (see inset). The data presented includes the measured voltage and measured current at the cell. There is clearly a lag just after the pulse in the measured potential applied to the cell in comparison with the requested potential when the 1 Hz filters are used. This type of impact on the data is most often a concern when studying fast transient processes via fast potential or current pulses or fast scan cyclic voltammetry or when using Auto Current Range under certain conditions. The impact of filters in combination with the Auto Current Range setting is discussed in detail in the FAQ - How to Select the Appropriate Current Range Setting, which is also part of the *Instrument Properties* Technical Note series.

The effect of the sampling rate is also shown in **Figure 5.** The data acquisition rate decreases from the red, to green to yellow data series. If sampling at only 1 Hz or 1 point per second (yellow), the impact of the filter goes unnoticed. However, when sampling every 0.5 s (green), the effect of the filter is seen. The impact of the filter is

even more evident when collecting data every 0.1 s (red).
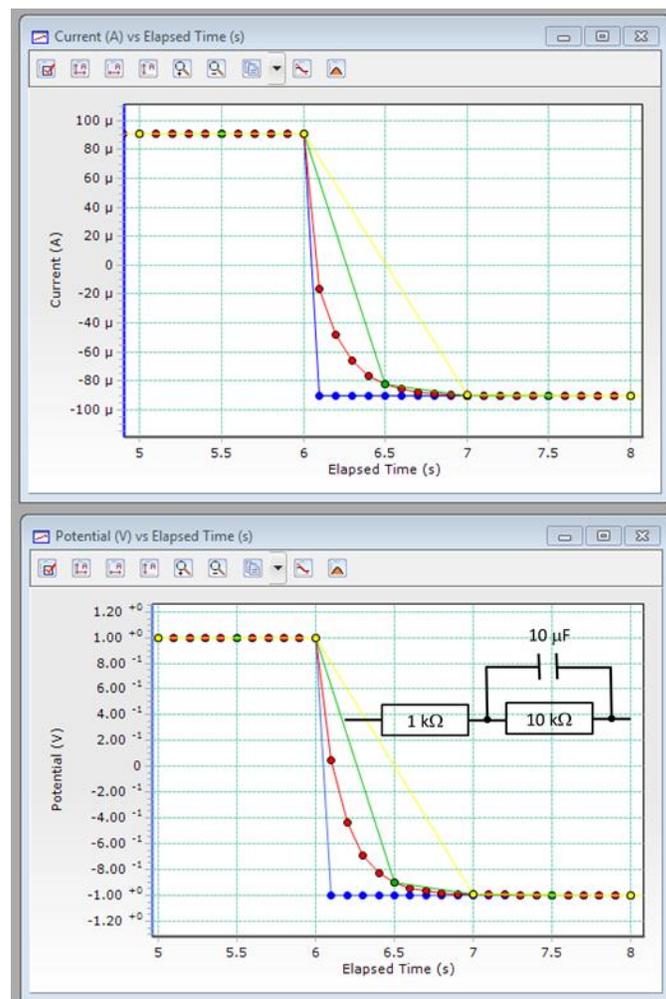

Figure 5: Current vs. Time and Potential vs. Time plots for Recurrent Potential Pulses applied to an AC Dummy Cell (inset) without E and I Filters and a Time Per Point of 0.1 s (blue) and with E and I Filters and a Time Per Point of 0.1 s (red), 0.5 s (green) and 1 s (yellow).

Effects Due to Bandwidth Limit Setting

Note that the E and I filters do not affect the speed of the control loop that applies the stimulus to the cell in the form of current or potential, but only filter the measured response just before it is digitized. The Bandwidth Limit setting is what affects the control loop speed. If observing fast pulses, it should be set at the highest frequency that allows the cell to remain stable. Leave the E and I filters set to "none" while determining this value, and decrease the sampling rate until the transition between the applied levels can be observed. Once the

optimal Bandwidth Limit is determined, use **Equation 1** to select the filter settings based on the rise times observed. Then use all of these settings in the actual experiment.

Summary

The E and I Filters can be used to remove noise from the analog signal measured at the cell, substantially improving the appearance of the data and making subsequent data analysis more straightforward. Caution in selecting the appropriate filter should be taken when studying fast transient processes and when using Auto Current Range. However, slow scan rate experiments, which are often employed for measuring low currents that are especially susceptible to noise, are rarely impacted negatively by the use of these filters. Selecting the appropriate sampling rate for the filter's cutoff frequency makes it possible to determine if a given set of filters is negatively impacting the experiment.

We suggest that users begin by running an experiment using the default E and I Filters. Currently, each Action in VersaStudio defaults to filter values considered to be the most appropriate for that type of experiment and the cells typically studied by the experiment. This setting is designated as "Auto", which can be used as a starting point. If the results appear noisy or appear to be negatively impacted by the filters, then the user should manually adjust the filter settings. It is generally recommended that the E and I Filters be set to the same level.