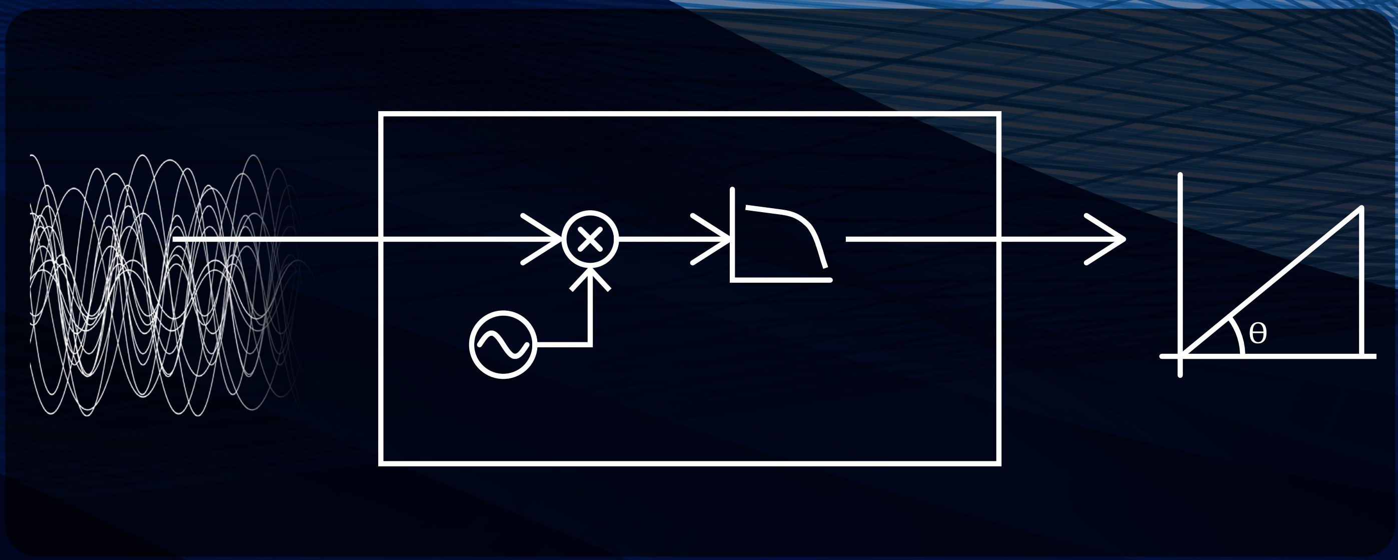
How to Choose the Right Lock-in Amplifier



Lake Shore
CRYOTRONICS

Introduction

Lock-in amplifiers are important tools for test engineers and material researchers because of their unique ability to precisely measure signals that are otherwise too small to detect amidst noise and other interfering signals. This singular capability makes them indispensable in a wide range of low-level measurement applications, from fundamental research in material science and engineering labs to product testing and development by electronic component developers and manufacturers.

In addition, lock-in amplifiers are increasingly playing a vital role in advancing research and innovation in various rapidly evolving fields, such as in the characterization and testing of quantum computing devices, including superconducting and topological qubits, as well as analyzing signals from quantum sensors. Plus, as electronic devices continue to get smaller, lock-in amplifiers play a key part in enabling researchers to precisely measure small signals in nanoscale structures, such as nanowires, nanotubes, and nanoelectromechanical systems, as well as single-electron transistors, quantum dots, and nanoscale sensors.

Because they improve measurement quality by enhancing the signal-to-noise ratio (SNR) and enabling phase-sensitive detection, lock-in amplifiers enable you obtain more precise and therefore repeatable measurements. Advanced features, such as programmable hardware and software filters and the ability to identify and measure multiple reference frequency harmonics, enable you to use them in an even wider range of highly complex measurement applications.

When used in less-complex measurement applications, if you're new to lock-in detection technology and typical lock-in products, you may find it difficult or confusing when researching and evaluating lock-ins for purchase. This paper aims to help simplify the selection and buying process.

We'll examine:

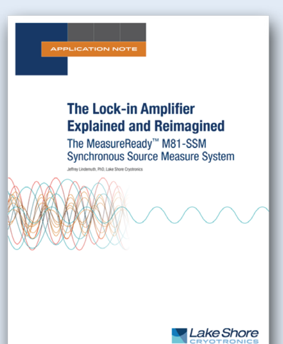
- The benefits and standard functions of a lock-in amplifier
- The different types of lock-in amplifiers available today
- Key considerations when choosing a lock-in amplifier
- Steps involved in evaluating and qualifying a lock-in amplifier
- How to overcome the learning curve when using lock-in amplifiers
- Finally, examples where a lock-in amplifier alone may not be the complete solution

The benefits and standard functions of a lock-in amplifier

A lock-in amplifier is a versatile instrument designed to measure weak signals that are obscured by noise and often also DC offsets. They do this by measuring very low amplitudes of the frequency of interest in the presence of large broadband noise and large spurious signals at other frequencies. They selectively extract signals with the same frequency and phase as a known reference signal using phase-sensitive detection.

This reference signal, which is typically generated using an internal oscillator or externally using some other modulation equipment, has a specific frequency and phase compatible with the samples and signals to be measured. The lock-in process begins with the input signal containing the desired weak signal of interest combined with the reference signal being fed into the lock-in and then amplified and fed into the digital phase sensitive detector (PSD). The PSD performs a multiplication process, which is a de-modulation process, resulting in the production of sum and difference frequencies as well as phase and amplitude information. The desired signal having the same frequency and phase as the reference signal is then reported as the measured X amplitude and Y phase results.

As for the lock-in amplifier output, it is a voltage proportional to the amplitude of the desired signal, which is now separated from the noise. The output also provides phase information relative to the reference signal, which can be useful in various measurement applications.



Learn a better way to extract signals from noise in our app note: The Lock-in Amplifier Explained and Reimagined

The different types of lock-in amplifiers available today

Evaluating lock-in amplifiers for test and measurement and material research applications involves ensuring that the equipment meets the specific requirements of your experiments or testing setup. But before you do, understand that there are different lock-in product types available. Here are the most common ones:

Single-input lock-in amplifiers
These are dedicated instruments designed specifically for lock-in voltage and in some cases, current detection. They are highly specialized and are ideal for applications requiring high precision and flexibility for low signal detection, particularly when measuring weak photonic signals, small changes in resistance, or signals from piezoelectric devices. They are also good for phase-sensitive measurements when studying material properties that depend on the phase relationship between an excitation signal and the response.

Multichannel lock-in amplifiers
These lock-in types can process signals from multiple inputs simultaneously, making them suitable for experiments that require measurements from several sources at once or need to monitor multiple harmonics of multiple signal channels. They are particularly useful for experiments or test applications where you need to measure several parameters or samples at the same time and you're looking to increase throughput and efficiency. They are also ideal for complex characterization or testing applications because they allow the measurements to be made under various conditions by measuring multiple frequencies concurrently.

Lock-in amplifiers with built-in programmable voltage and current sources

Most lock-in amplifiers come with an integrated signal source, simplifying the setup by providing both the excitation signal for the sample and the detection mechanism in one unit. These are particularly useful for impedance spectroscopy, which involves studying the frequency response of samples by applying an AC signal and measuring the resulting current or voltage. They are also useful for investigating electrochemical processes, where they can supply an AC voltage to the electrochemical cell and measure the AC response.

Multichannel systems for sourcing and measuring with built-in digital lock-in

Lock-in amplifiers are primarily voltage measurement devices, and to add current and resistance measurements for low-level material or device characterization generally requires additional source and V-to-I conversion instruments as well as gain and filter enhancement preamplifiers. But it is possible to get such capabilities built into the same measurement system itself with the lock-in capabilities implemented digitally. Such is the case with the Lake Shore M81-SSM synchronous source measurement system, a type of multichannel system that combines DC and AC sourcing with DC and AC measurement and enables continuous data sampling on every connected channel. This high degree of synchronization between source and measurement means that the M81-SSM can be used to make lock-in measurements that can extract very weak signals from noisy backgrounds, and each channel can be set to perform AC, DC, or lock-in measurements. The higher sensitivity for lock-in detection is particularly useful for characterizing low-power or low-resistance electronic devices.

Key considerations when choosing a lock-in amplifier

Choosing a lock-in amplifier for your application involves several steps to ensure that it meets the specific requirements of your experiments or testing setup. Here is a list of considerations when evaluating a lock-in amplifier:

The smallest and largest signals you need to measure (both current and voltage)

Determine the range of signal amplitudes and the resolution to which you need to measure the smallest and largest signals. This information is often found in product datasheets. In specifications, measurement

sensitivity (given in μV/nV and μA/nA) and resolution (given in number of digits or ADC bits) should be listed in terms of absolute accuracies traceable to a specific standard and ideally include offsets, time, and temperature drift adders so you obtain a realistic understanding of lock-in instrument and total system uncertainties to ensure your application needs are satisfied.

Typical lock-in amplifiers referenced in many research papers have varying levels of accuracy, noise, and drift specifications and are typically specified around 1% absolute accurate to a given voltage or current standard. While sufficient for many applications, a best-case accuracy and repeatability specification of 1% may not provide adequately precise or repeatable/reproducible results over time. This is why an entire system error budget should be established. Once it is, you can determine each instrument's measurement error contribution and suitability for each given test setup.

Also note the input resistance specifications of the lock-in and whether there is the potential for the lock-in affecting your measurements due to shunt loading of higher-resistance samples. For example, connecting a lock-in with 10 MΩ input impedance directly across a 100 kΩ resistance sample would alone reduce the true signal amplitude by 1%. For a 1 MΩ sample, the loading effect would be 10%, and so on. Preamplifiers with higher input impedance or alternate input modules for certain lock-ins should be chosen based on this specification in addition to maximum voltage, noise, and other key specifications noted above. The ideal case would be to choose the highest input impedance lock-in that also meets noise and other requirements to avoid use of additional preamplifier add-on instruments.

The signal frequency range you'll be working with
Lock-in amplifiers have specific frequency ranges over which they operate. These can vary, but typically they are from mHz to hundreds of kHz with some reaching MHz and even GHz frequencies for highly specialized RF applications. Choosing a model with a sufficient minimum and maximum frequency range allows you to use it in a variety of applications, from low-frequency measurements typical in some material science experiments to higher frequencies used in other scientific and engineering fields. The maximum operating frequency must encompass the highest harmonics of the reference signal so as not to attenuate or otherwise distort those harmonics.

The lock-in, in the simplest description, is an AC voltmeter that measures at one frequency both the amplitude and phase of the input. In most cases, a DC signal cannot be measured, which is both a benefit and a limitation of the lock-in in some applications. The lock-in's inherent ability to reject DC signals, while a benefit in the case of unwanted thermal offsets, can be limiting in applications where DC biasing is required because typical lock-ins cannot measure DC signals separately from the AC signals at the reference frequency. There are also cases where high levels of DC mixed into the AC signals of interest can overload and even damage an AC lock-in input amplifier and some commonly used filters and preamplifiers as well.

Certain newer digital lock-ins have two voltage inputs, and the coupling of the input can be AC or DC. Because these lock-ins, like most modern lock-ins, operate using digital signal processor (DSP) technology and can work to very low frequencies, the DC coupled input is often required (even while the lock-in itself is measuring an AC signal).

Another thing to keep in mind: The frequency range you need can differ depending on application. For example, a 2D material characterization application may have different frequency ranges versus the frequencies required for testing fully constructed electrical devices. Graphene, transition metal dichalcogenides (TMDs), and other types of 2D materials often exhibit unique properties that are frequency dependent. Characterizing such materials might require very low to high frequencies depending on the physical phenomena under investigation. You may require low frequencies to determine charge transport, conductivity, and dielectric properties, but high frequencies might be necessary for investigating optical properties, plasmonic behavior, or fast electronic transitions.

Also, in the case of testing electronic components to ensure reliability, the required operational frequency range of the lock-in is often determined by the operational frequency range of the device itself, such as low frequencies for power electronics. And it may also be determined by the nature of the tests, which might include noise measurements, impedance spectroscopy, or harmonic distortion analysis. These tests generally cover a broader frequency range than material characterization, as they need to simulate operational conditions the device may encounter in real-world applications.

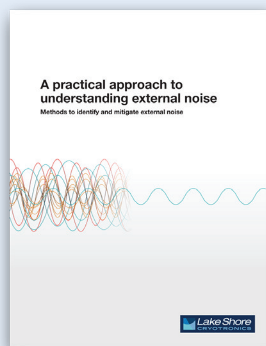
Data acquisition and transmission speeds
The bandwidth and time constant — essentially, a measure of the response time of the lock-in amplifier's low-pass filter and how long it takes to "settle" to a steady state output after a change in the input signal — affect how quickly it can accurately respond to signal changes. If the signal changes rapidly, a shorter time constant (higher bandwidth) may be necessary to track these changes accurately. For signals that change slowly or when measuring very low-level signals where noise is a significant concern, a longer time constant (lower bandwidth) would be more appropriate.

Separate from the signal data acquisition speed, you should also consider transmit data rates to remote PC controllers, especially in streaming and applications studying time-varying signals. Lock-in technology that tightly synchronizes data collection and supports streaming can be useful in these situations. It can also be beneficial when you are measuring multiple devices and need consistent data under identical conditions across all channels. Channel-to-channel synchronization may require individual ADCs per input channel versus the more typical multiplexed single ADC-type approach to adding measurement channels.

The acceptable level of noise in your application
Assess the input and complete system noise levels of the lock-in amplifier and ensure they are low enough for your applications to achieve a high SNR.

Applications requiring a high SNR can include those involving impedance, photoluminescence, or magnetic resonance spectroscopy, electrochemical measurements, and optoelectronic device characterization. In contrast, there are also characterization applications where it is less critical, such as some DC electrical characterization environments, high-power device testing setups, or high-frequency RF/microwave characterization applications. Additional preamplifiers add noise to the signal chain and must be factored into the total system noise analysis and budget versus needs.

How much phase sensitivity you require
Ensure the lock-in amplifier can accurately measure the phase difference between the reference signal and the signal being measured. Phase-sensitive measurements are particularly important for certain spectroscopy applications where you need to extract spectral features and identify spectra components. They are less relevant for DC electrical characterization or high-power device testing, where factors like dynamic range and distortion characteristics are more important. One thing to keep in mind for applications requiring highly accurate phase sensitivity: Environmental conditions such as temperature stability, electromagnetic interference, and signal attenuation can adversely affect the lock-in's ultimate usable and repeatable sensitivity and accuracy.

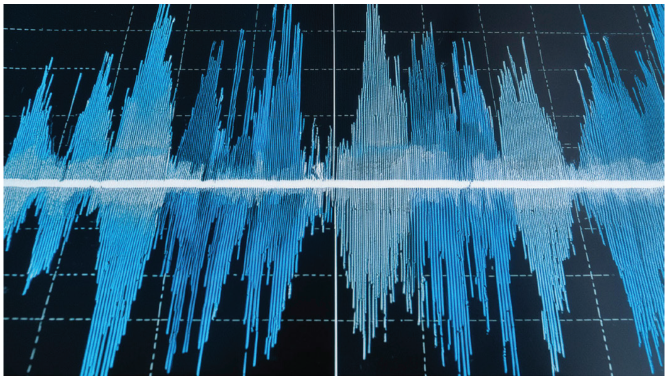


Want to ensure the lowest possible noise levels for your experiment? Download A practical approach to understanding external noise

Steps involved in evaluating and qualifying a lock-in amplifier

Step 1: Define your requirements

- Determine the smallest and largest DC and AC signals you need to measure and the range of signal amplitudes you need for lock-in detection.
- Identify the frequency range of the signals (fundamentals and harmonics) you will be working with. Lock-in amplifiers have specific operational frequency ranges, so choose one that covers your needs.



- How fast will you need to acquire (as well as transmit) data? The time constant and bandwidth of the lock-in amplifier affect how quickly it can accurately respond to changes in the signal.
- Assess the noise levels of the lock-in amplifier and ensure they are low enough for your applications to achieve a high enough SNR, and also determine the level of hardware and software filtering required.
- Determine the types of inputs and outputs you need (e.g., voltage, current, digital, analog) for interfacing with other equipment and/or integrating into larger characterization or test setups. Along with types of inputs and outputs, think about your requirements for future expansion and the need for additional input channels later.

Step 2: Evaluate technical specifications

- Look for lock-in amplifiers with frequency ranges that cover your signals of interest. Ensure that the range covers the fundamental frequency as well as any related modulation frequencies of the signals you intend to measure.
- Assess the dynamic range and sensitivity specifications to ensure they meet your amplitude range requirements. When comparing specs between different models, dynamic range might be specified in terms of a ratio (e.g., 1:1,000,000) or in decibels (dB).
- Look at accuracy specifications, expressed as plus or minus a percentage vs. time and calibrated temperature. Even if you don't care about an absolute accuracy to a known standard, you will likely want successive measurements to be within some range of precision so you can reproduce results over time. Sufficient accuracy specifications ensure sufficient repeatability. If you require repeatability to 1%, then you should have accuracy of roughly half of that, or 0.5%, because the variation can span ± the accuracy specification, for +0.5 to –0.5% or a total of 1%. And if you have more than one instrument in your system, then you need to add each instrument's contribution to errors (which reduces total system accuracy).
- Check the phase sensitivity specifications, typically expressed in degrees or milliradians, to ensure they meet your measurement precision needs. The phase sensitivity specification will tell you if it can accurately measure the phase difference between the reference signal and the signal being measured.
- Evaluate the data acquisition rates and transfer rates supported by the lock-in amplifier to ensure they are sufficient for your application.

- Compare noise levels among different models and choose one with low input-referred noise for accurate measurements. These specifications are typically expressed in terms of voltage or current noise density (e.g., nV/√Hz or pA/√Hz). Lower input-referred noise levels result in higher SNR measurements, particularly when dealing with weak signals or low-level measurements.
- Look at which type of filtering is available (e.g., low-pass, band-pass) and their adjustable parameters to match your signal processing needs. Adjustable filtering settings enable you to optimize noise rejection while preserving the integrity of the signal of interest.
- If measuring harmonics of the fundamental frequency is necessary, check the lock-in amplifier's harmonic detection capability for detecting and measuring these signals and ensure the highest harmonics do not exceed the maximum input frequency and processing ratings.

Step 3: If possible, test it out
If the manufacturer can provide a demo unit, request it and conduct bench tests to verify performance specifications within specific conditions. In addition, test the lock-in amplifier within your research or measurement applications to ensure it meets all practical requirements. You will want to verify performance across the required frequency range within your actual setup, which can be done using an oscilloscope, frequency counter, or spectrum analyzer to monitor and verify the frequency response.

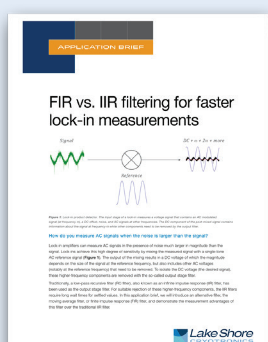
Step 4: Find out if post-sales support is available
Consider the level of technical and application support provided by the manufacturer, including availability of user documentation and if their in-house experts can be reached easily and can answer application-specific questions and help with troubleshooting. Similarly, check the warranty period and service options in case of malfunction or the need for calibration.

Step 5: Compare costs, accounting for the total system
Evaluate the cost of the lock-in amplifier in relation to your budget and the return on investment by considering the performance improvements it brings to your applications. However, be sure to look at the total cost of ownership for the entire system, too. Additional costs relating to accessories, software, or necessary upgrades may impact how much you spend in the long run.

How to overcome the learning curve when using lock-in amplifiers

To help you better grasp how a lock-in amplifier works and how it can benefit your specific application, you may want to:

- **Familiarize yourself with the basics.** Start by learning the fundamental concepts and principles of lock-in amplifiers, such as synchronous detection, phase-sensitive detection, and time constants.
- **Carefully read the user manual provided by the manufacturer.** It will contain essential information on the instrument's features, specifications, and proper operation.
- **Search the web for online tutorials, application notes, and other lock-in amplifier resources.** These materials can provide valuable insights and practical examples of how to use and implement lock-in amplifiers in various experimental setups.
- **Get hands-on practice.** Experiment with the lock-in amplifier using a simple test setup, starting with basic measurements and gradually progressing to more and more complex experiments.
- **Consult with experienced users.** Colleagues, professors, or others in your field who have experience using lock-in amplifiers can provide valuable advice on best practices and techniques to employ in your application.
- **Attend workshops or training sessions.** Some manufacturers or institutions offer workshops, webinars, or training sessions on lock-in amplifiers. Taking part in these can help you deepen your understanding of lock-in usage and learn from experienced professionals.
- **Develop a process.** When setting up and configuring the lock-in amplifier for your experiments, a process-based approach will help ensure all necessary steps are followed, whether it is properly connecting cables, selecting the appropriate input and output settings, configuring the reference signal, adjusting the time constants and filters as needed, etc.
- **Follow a troubleshooting process.** If you encounter an issue during experiments, identify potential sources of error and address them one at a time so you can quickly resolve the problem.
- **Keep a record.** Document what you've learned in your experiments, recording settings and observations to help you track your progress and to reference during future experiments.


APPLICATION BRIEF

FIR vs. IIR filtering for faster lock-in measurements

When characterizing a device, you often look for a small response to some sort of stimulus. Frequently, this is being done in the presence of a DC offset as well as a lot of noise — which often can be larger than the signal itself. The typical way to obtain the sought-after level of response is to use a lock-in amplifier.

The output stage filter is a key component of lock-in detection. Traditionally, an infinite impulse response (IIR) filter has been used as the output filter on lock-in amplifiers. The issue is, for suitable rejection of higher-frequency components, IIR filters require long wait times for settled values.

In this app brief, we examine using a finite impulse response (FIR) filter and compare the two filtering methods.

Read FIR vs. IIR filtering for faster lock-in measurements

Examples where a lock-in amplifier alone may not be the complete solution

A lock-in amplifier is a powerful instrument for measuring weak signals buried in noise. But, at times, they can be expensive and rather complex to use, and in some cases, you may not even need one. For applications with lower performance requirements, other measurement techniques may be more suitable and cost-effective.

For instance, lock-in amplifiers are not well-suited for measuring fast signals with rapidly changing frequency or phase components. This is because the time constants and low-pass filtering in lock-in amplifiers inherently introduce a delay in the measurement, possibly preventing them from capturing fast signal variations.

In addition, lock-in amplifiers work best with sinusoidal signals, and for non-sinusoidal or complex waveforms, they may not provide the desired measurement accuracy. If your application involves these types of waveforms, alternative techniques such as time-domain or Fourier analysis may be more appropriate.

It can also be challenging to use lock-in amplifiers in applications where the reference signal frequency is unknown or unstable. You will require a stable and known reference frequency for synchronous detection, and if it's not present, you may require additional signal processing techniques to track the frequency.

And there's also the dynamic range to consider. If the signals being measured have a large dynamic range containing a wide range of amplitudes, the lock-in amplifier may not be able to accurately capture the full range without saturating or introducing distortion. In such cases, you may need high-dynamic-range measurement instrumentation or additional signal conditioning.

Learn how to overcome the challenges of characterizing ultra-small structures in our tech note: A New Approach to Low-Level Measurements of Nanostructures

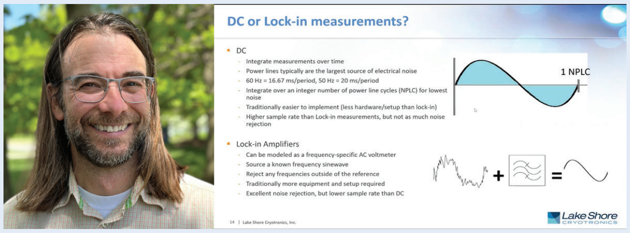
An innovative architecture for coordinating low-level measurements from DC to 100 kHz

The Lake Shore MeasureReady™ M81-SSM synchronous source measure system provides a confident and straightforward approach for advanced measurement applications. The M81-SSM eliminates the complexity of multiple function-specific instrumentation setups, combining the convenience of DC and AC sourcing with DC and AC measurement, including a lock-in's sensitivity and measurement performance.

Highly adaptable for a range of material and device research applications, the extremely low-noise system ensures inherently synchronized measurements from 1 to 3 source channels and from 1 to 3 measure channels per half-rack instrument. Also, when its BCS-10 and VM-10 modules are combined, the system offers differential wiring to the sample — a proven method of minimizing environmental noise pickup that can interfere with low-level measurements.

Learn more about the M81-SSM

Webinar: Practical Considerations for Reliable Characterization of Electrical Devices



Webinar is a must-see for high-quality, repeatable measurements

This webinar with MRS covers the steps you need to ensure reliable characterization of electrical devices and materials — particularly when characterizing at cryogenic temperatures.

Learn how to:

- Reduce the impact of noise, self-heating, and other parasitics
- Simplify connections to the device under test, including ground connections
- Ensure simultaneous measurements when testing multiple samples
- Minimize ground loops and crosstalk on instrument cabling

Your presenter: Jason Chonko

Watch the webinar

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