LIQUID
INSTRUMENTS

Measuring phase with precision: a guide to phase measurement methodologies

Three ways to measure phase accurately and efficiently

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Why measure phase?

Accurately measuring phase is a critical aspect of many scientific and engineering applications. Whether you are delving into cutting-edge research, developing sophisticated communication systems, or troubleshooting electronic circuits, the ability to measure phase with precision is indispensable.

Scientists and engineers make phase measurements to achieve nanometer-level precision in measuring distances and shapes, which is essential to interferometry applications. Phase information helps us map terrain in LiDAR, analyze chemicals with spectroscopy, perform biomedical imaging, and more. Phase control and measurement enables scientists to perform precise material removal in manufacturing, maintain secure communication through quantum key distribution (QKD), transmit high-speed data over long distances through fiber optic communications, and support many other nonlinear optics applications.

Phase measurement allows for precise control of timing in communication systems, enabling the reliable transfer of information over vast distances. In electronics and circuit design, it facilitates troubleshooting and optimization, ensuring the efficiency and functionality of devices.

Accuracy down to the μcycle

It's important that your measurement device has enough precision to get meaningful results. Here, we're using the Moku Phasemeter to measure phase with part-per-million accuracy.

Understanding phase

Phase is a fundamental concept that helps describe the behavior and characteristics of various types of signals, waves, and oscillations. Accurately measuring, controlling, and understanding phase is essential for anyone working in optics and photonics research, as it helps shape the behavior and applications of light and other electromagnetic waves.

What is phase in signal processing?

Phase represents the position of a point in a waveform relative to its cycle. It is typically measured in degrees or radians and describes the fraction of a complete cycle at a given instant.

To visualize phase, think of a sinusoidal waveform, like a sine or cosine wave. The phase indicates how far along the wave has progressed within one complete cycle, ranging from 0 to 360° (or 0 to 2π radians).

Phase can also be thought of as a measure of time within a periodic waveform. A phase of 180° corresponds to half of one cycle, while 360° completes a full cycle.

Relative phase is the difference in phase between two waveforms. A phase shift corresponds to a time delay in a periodic waveform. For example, a phase shift of 180° introduces a time delay of half a cycle.
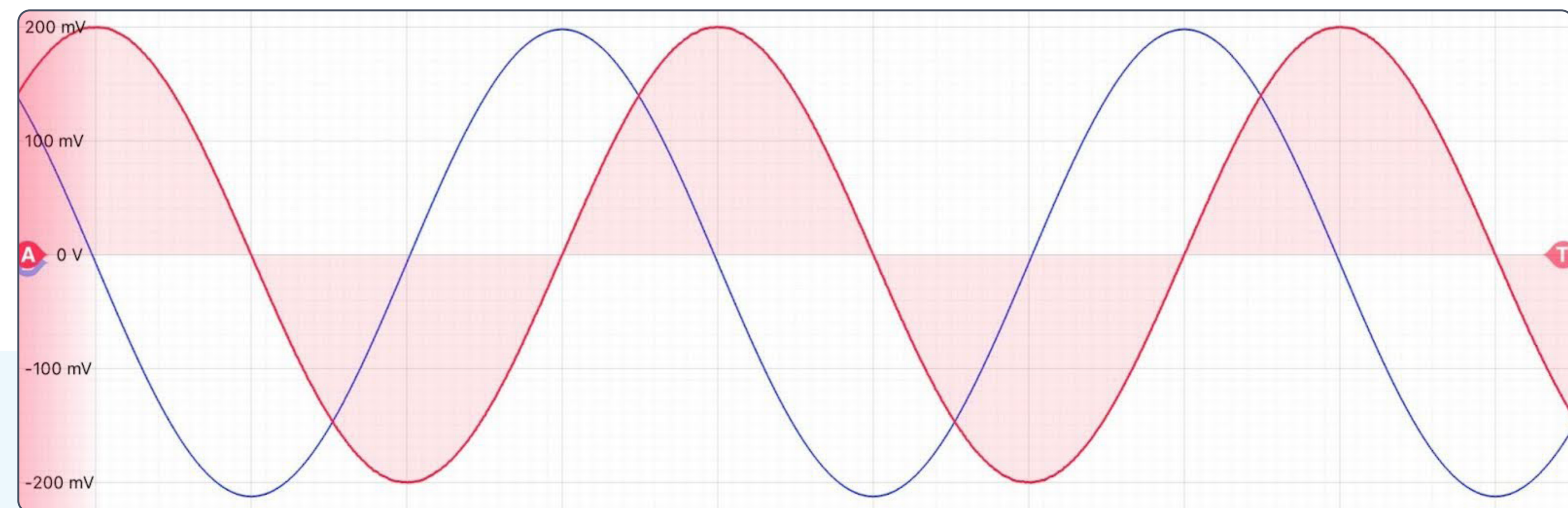
Observe the relative phase shift between two periodic signals. Although the red and blue sinusoids have the same amplitude and frequency, they are phase shifted by 90°. When the red function reaches a maximum or minimum in amplitude, the blue function is at zero, and vice versa.

Phase measurement applications

Biophotonics: Phase-sensitive imaging techniques allow scientists to visualize cellular structures and processes.

Fiber optic communications: Maintaining phase coherence in optical signals is essential for high-speed data transmission over long distances.

Interferometry and metrology: Phase measurement enables incredibly precise measurement of distances, shapes, and other properties with nanometer-level accuracy, essential for aerospace applications.

LiDAR and remote sensing: Phase measurements enhance the accuracy of LiDAR systems for applications like autonomous vehicle navigation.

Materials characterization: Engineers can characterize material properties by exciting samples with light and measuring the response.

Nonlinear optics: Phase control enhances efficiency of some nonlinear optical processes, such as laser spectroscopy.

Quantum optics: Phase manipulation and measurements are central to generating, controlling, and measuring quantum states.

Ultrafast optics: Applications such as femtosecond laser technology rely on precise phase control.

The LISA mission
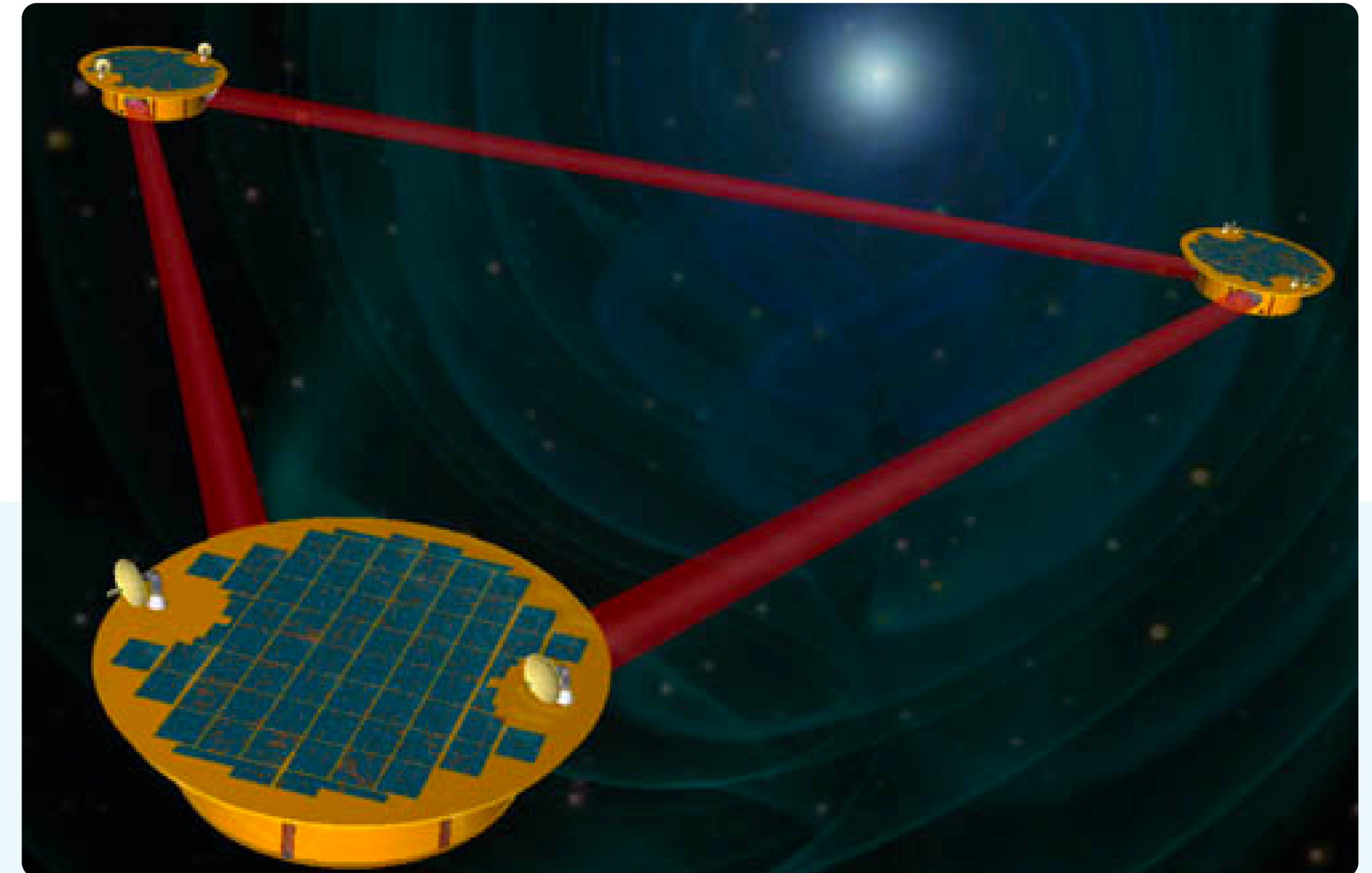
NASA's Laser Interferometer Space Antenna (LISA) mission is an example of spaceborne interferometry where precise phase measurements are crucial.

Phase measurement basics

Types of phase measurements

Absolute phase measurement: The phase of a signal is measured with respect to an absolute reference, such as a known standard.

Relative phase measurement: The phase of a signal is measured by comparing the phases of two waveforms of the same frequency.

Common phase measurement challenges

Noise and jitter: Noise and random fluctuations can introduce uncertainties into phase measurements. This can be overcome with noise reduction and phase synchronization.

Nonlinearity: Nonlinear components can cause the signal's phase to deviate from its ideal behavior, making it critical to obtain precise phase measurements.

Phase wrapping and range: Some phase measurement techniques are limited to a single cycle (-π to +π or 0 to 2π), which leads to phase wrapping and discontinuities when this range is exceeded. Optical experiments often require measurements of unwrapped or continuous phase.

Variations in frequency: Variations in the frequency of a signal can affect phase measurements — this can be overcome by using phase-locked loops (PLLs).
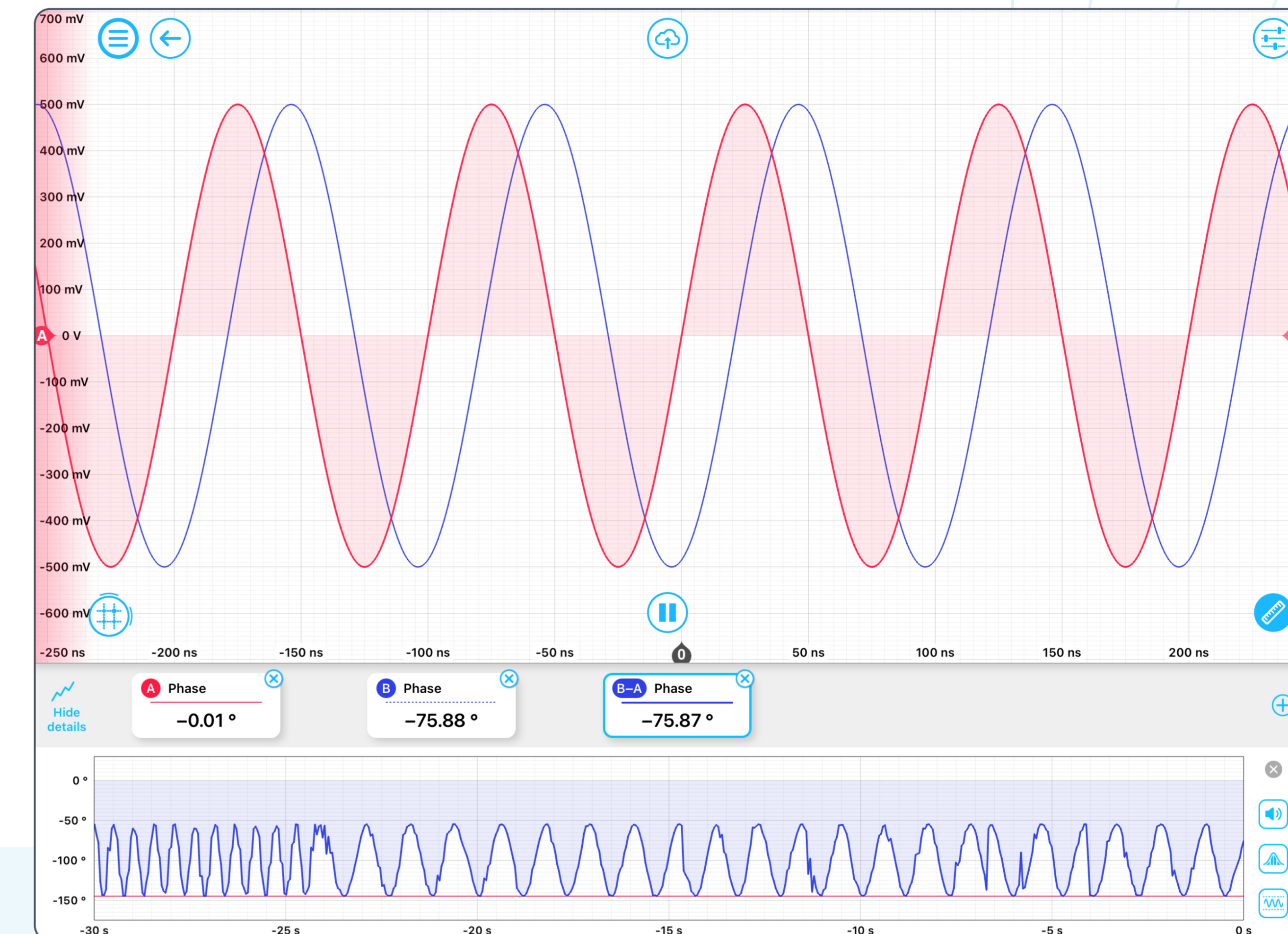
Measuring phase with an oscilloscope

Principle of operation

Oscilloscopes are one of the most common test instruments available, displaying voltage signals in the time domain. Engineers and scientists use oscilloscopes to compare the phase relationship between two or more signals and make demodulation-free phase measurements.

Benefits of using an oscilloscope for phase measurement

- Using an oscilloscope is a simple and accessible method to measure phase.
- Some oscilloscopes contain built-in waveform generators to compare both transmitted and received signals to compare phase between them.
- With digital, multi-instrument solutions like the Moku device family from Liquid Instruments, all instruments are digitally interconnected. There is no additional phase shift or loss between instruments due to cabling and adapters.

A simple and straightforward approach

Measuring phase with an oscilloscope is accessible and simple, but may not provide the level of precision needed for many applications. In this measurement with the software-defined Moku Oscilloscope, the relative phase of signals B and A oscillates over time due to the slow phase modulation on B.

Limitations and downsides

› With an oscilloscope, you're limited to wrapped phase measurements only.

› This technique provides a limited signal-to-noise ratio (SNR), and it is susceptible to jitter.

How can I improve the SNR of this measurement?

Add digital filters to your system to filter out noise. You can add infinite impulse response (IIR) filters or finite impulse response (FIR) filters in Multi-instrument Mode using FPGA-based Moku devices. We recommend adding a bandpass filter around your signal of interest.

Expanding functionality with FPGAs
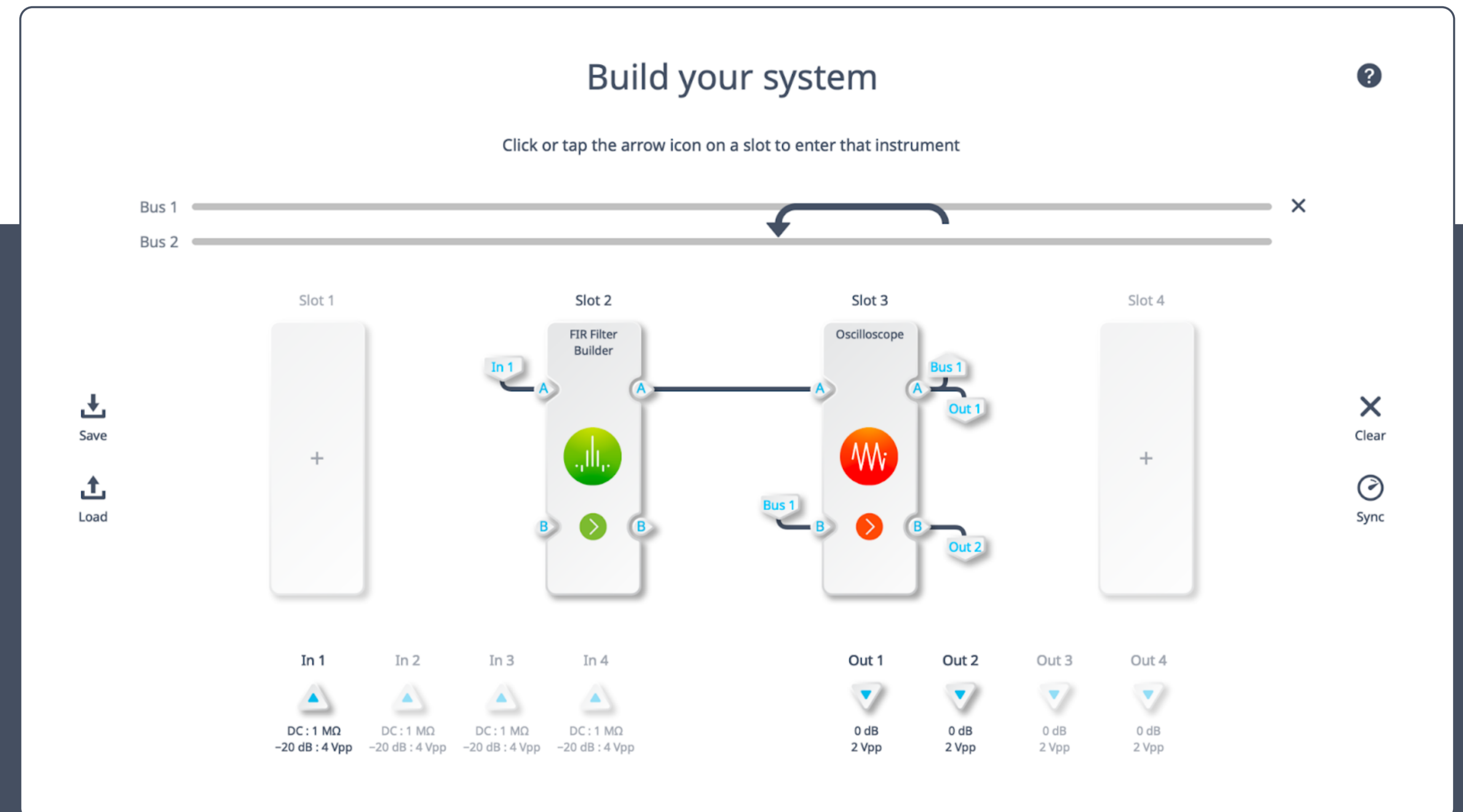
With reconfigurable FPGA-based technology like the Moku platform, you can quickly expand and adjust your test system to fit the needs of your experiment.

Measuring phase with a lock-in amplifier

Principle of lock-in amplifiers

A dual-phase lock-in amplifier like the one in Moku devices extracts weak signals from noisy environments by using two reference signals that are 90° out of phase. This allows you to precisely measure the phase and amplitude of signals.

Benefits of using a lock-in amplifier for phase measurement

- Dual-phase detection compensates for phase fluctuations over time, making the measurement more accurate.
- This method recovers both phase and amplitude information from your demodulated signal.
- The software-defined Moku Lock-in Amplifier offers built-in data logging and an embedded PID Controller to track and stabilize measurements.

Limitations and downsides

› The phase measurement wraps, making it difficult to use in applications like feedback control where large changes in phase are expected.

Lock-in amplifier block diagram
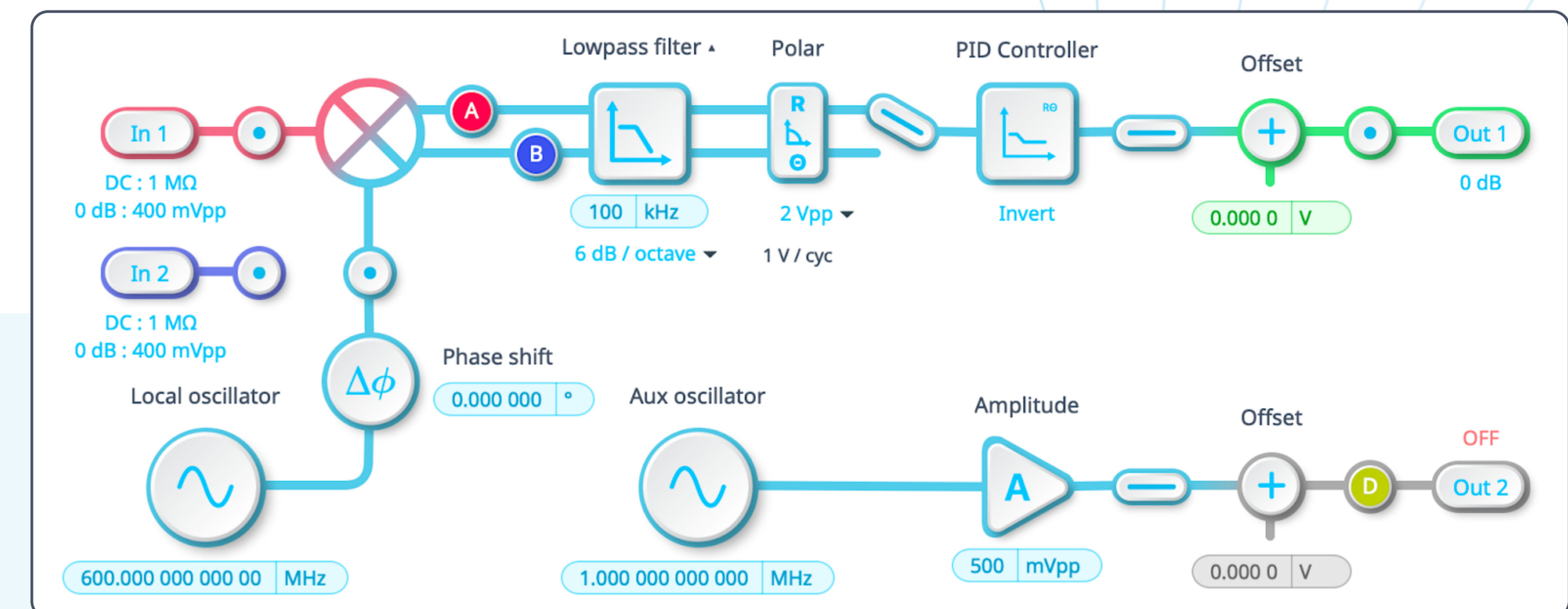
Not all lock-in amplifiers allow you to modify your reference source. Make sure your lock-in amplifier delivers the flexibility and performance needed for your current experiment, and that it can also cover future needs. The modern interface of the Moku Lock-in Amplifier is shown here.

Measuring phase with a phasemeter

How phasemeters work

A phasemeter uses a phase-locked loop (PLL) to provide high-sensitivity measurements of dynamic signals. Phasemeters allow for unwrapped, ultra-precise measurements of phase, while also tracking frequency and amplitude.
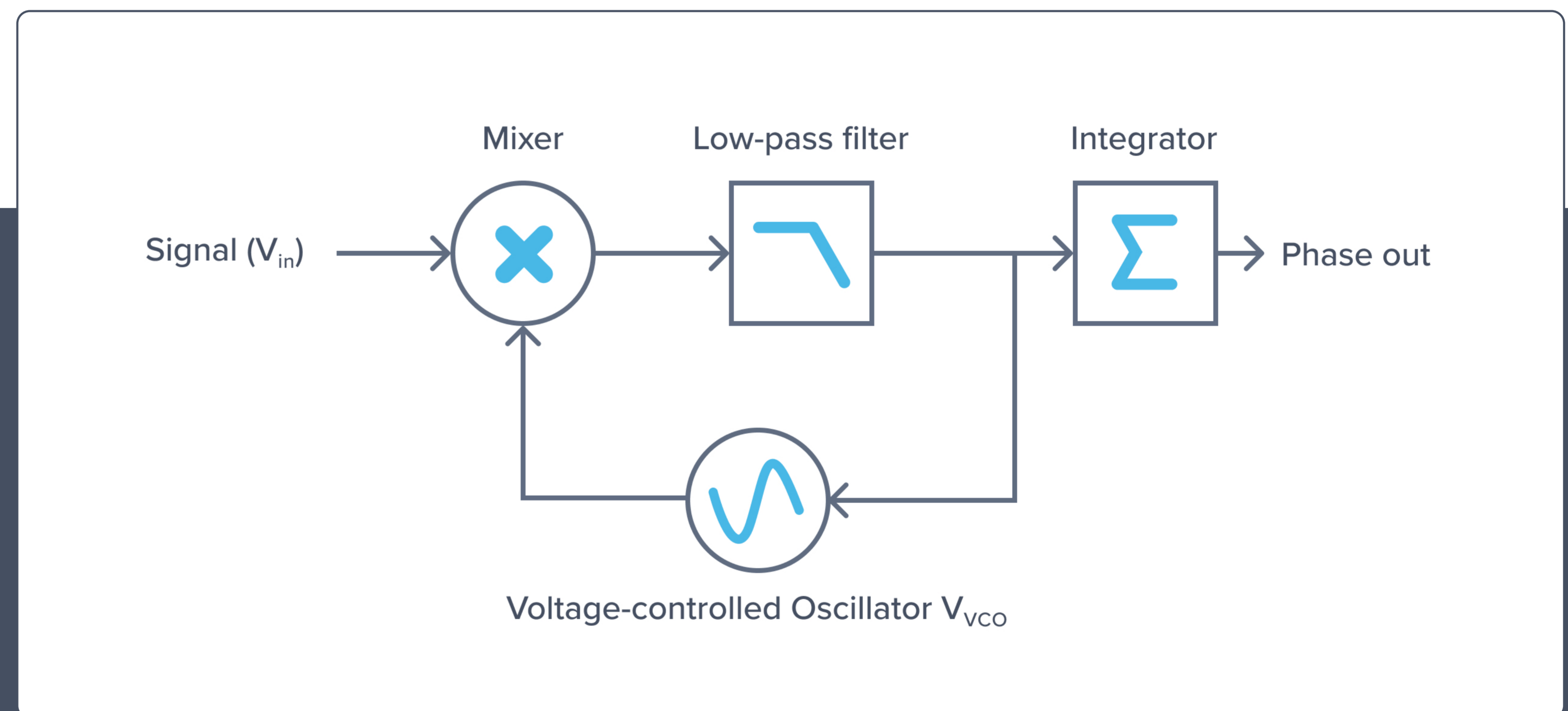
What's a PLL?

A PLL uses a phase detector to measure frequency mismatch. The goal is to lock an internal oscillator to the input signal, maintaining a constant phase relationship between the signals.

Want to learn more? Read about the principle of operations of the Moku Phasemeter here.

From the simplified Moku Phasemeter block diagram above, note how the output of the low-pass filter is fed back to form a closed-loop system.

Benefits of using a phasemeter for phase measurement

› Phasemeters are extremely sensitive and precise.
› It's easy and efficient to measure frequency, phase, and amplitude.
› You can output signals that are phase-synced to the inputs.
› Unlock greater insights with advanced functions such as power spectral density and Allan deviation measurement.

Applications

Free-space optical communication (FSOC): A phasemeter can track the phase offset between optical signals to implement coherent receiving.

Optical metrology: A phasemeter allows scientists to measure distance at the picometer level.

Limitations and downsides

› The system must maintain a lock — if the signal changes on a timescale faster than the PLL can track, the measurement can diverge. However, the system can relock after the disturbance has been removed.

Measuring power spectral density
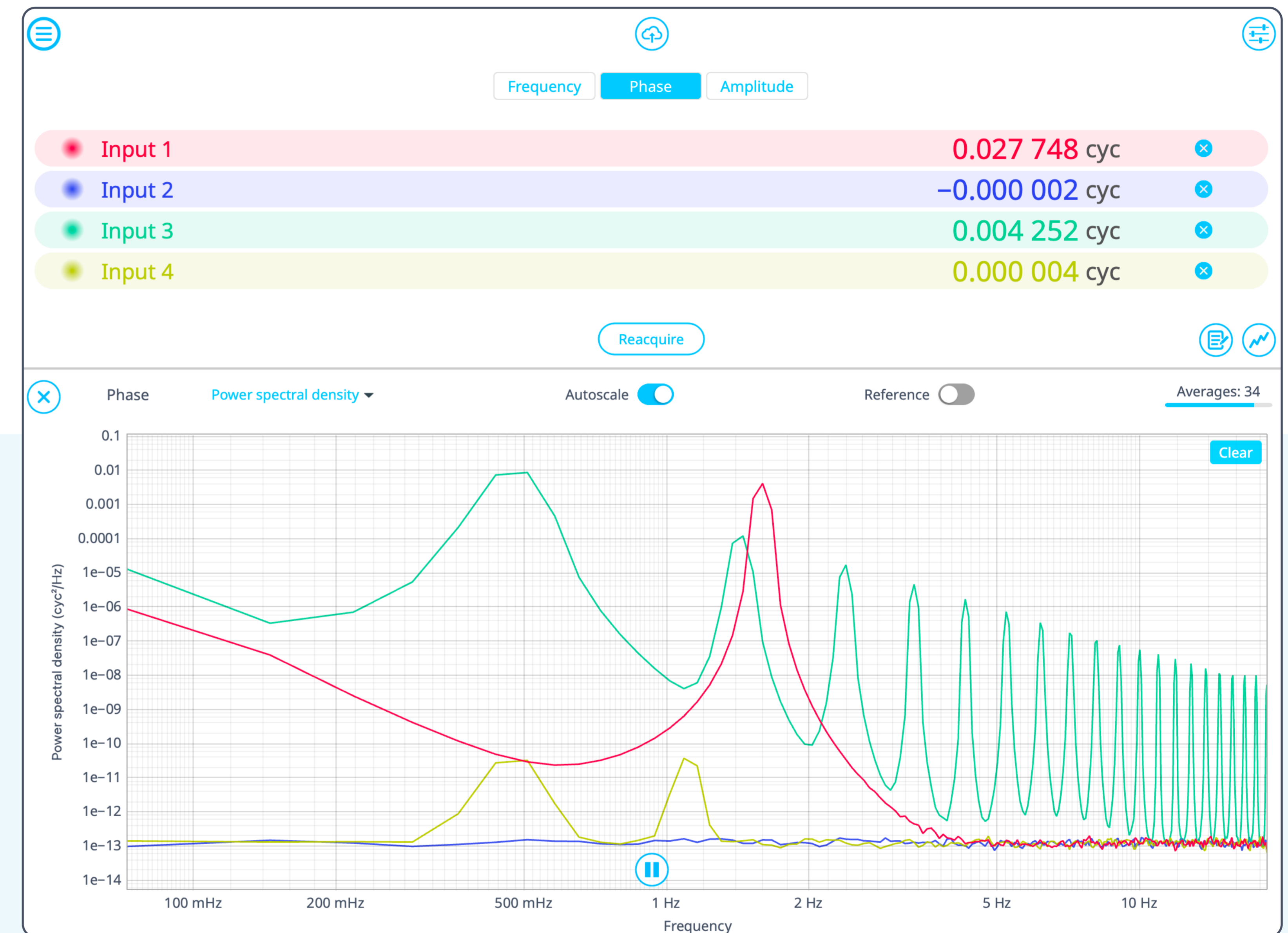
With the Moku Phasemeter, you can use built-in graphs to analyze data in real time.

Which method should you use?

When you need precise phase measurements, we recommend using either a phasemeter or lock-in amplifier.

Use a phasemeter when:	Use a lock-in amplifier when:
Your signal feeds a control system and you need unwrapped phase measurements.	You're dealing with gated or intermittent signals close to the noise floor.
You're measuring an ungated signal and precision is everything.	You value instantaneous readouts more than precision.

Measuring with Moku

While the best instrument for you depends on your specific environment, the closed-loop approach of the Moku Phasemeter provides exceptional linear dynamic range, while the Moku Lock-in Amplifier has a wide bandwidth and excels in noisy environments.

Other considerations

Determine your frequency range

Consider your frequency needs when choosing instrumentation. Moku devices come in three performance options:

	Lock-in Amplifier	Phasemeter
Moku:Pro	1 mHz to 600 MHz	1 kHz to 300 MHz
Moku:Lab	1 mHz to 200 MHz	1 kHz to 200 MHz
Moku:Go	1 mHz to 30 MHz	1 kHz to 30 MHz

Essential features and functionality

You'll likely need to log and analyze your data. Consider solutions like Moku that let you do everything in one place, with features such as:

- Allan deviation
- Amplitude spectral density
- Coherence tracking
- Data sharing
- Embedded oscilloscope and waveform generator
- Power spectral density

Measuring Allan deviation with the Moku Phasemeter
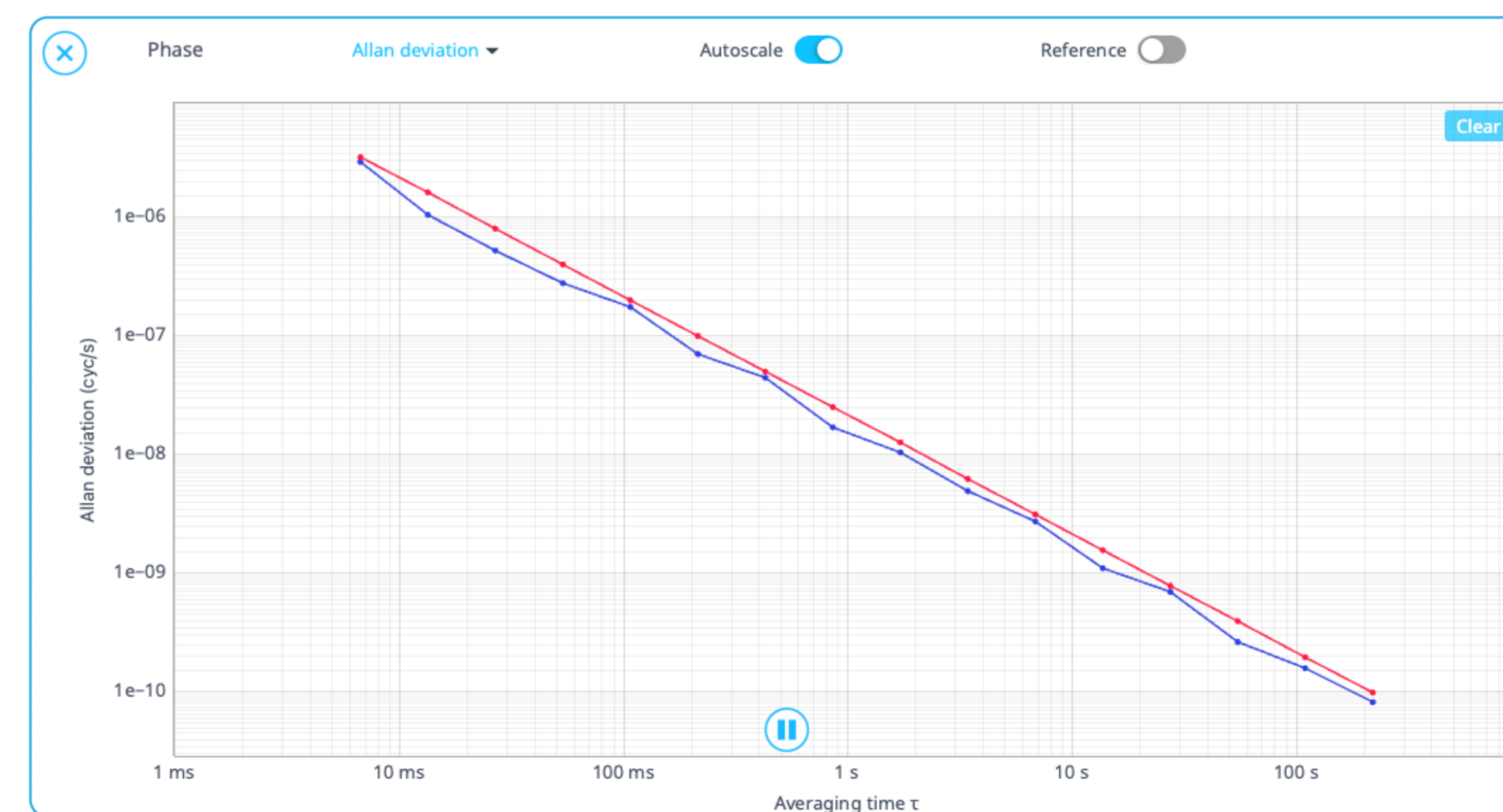
A new phase for test

When making precise measurements, it's important to consider multiple methodologies to ensure you choose the right instrumentation for your application. In this guide, you've learned:

• What phase is and why it's important
• Phase measurement applications
• The basics of phase measurement
• How to measure phase with an oscilloscope, a lock-in amplifier, and a phasemeter
• How to leverage flexible, FPGA-based Moku devices and software-defined instrumentation to conduct phase measurements with all three methods

Additional resources

For more information, check out these resources:

• Application note: Phase-locked loop frequency multiplier and divider use cases
• Application note: Phase detection with the Lock-in Amplifier and Phasemeter
• Application note: Measuring Allan deviation
• Video: Moku Lock-in Amplifier
• Video: Moku Phasemeter

Ready to get started?

Explore the software in demo mode or configure your hardware.

Questions?

Have product or technical questions? We're here to help.

To learn more about Moku products, visit liquidinstruments.com.

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