Moku:Pro Phasemeter

User Manual

The Moku:Pro Phasemeter measures phase with up to 6 µradian precision for input signals oscillating between 1 kHz and 300 MHz. Using a digitally implemented phase-locked loop architecture, it provides exceptional dynamic range and precision far exceeding the capabilities of conventional lock-in amplifiers and frequency counters. Moku:Pro Phasemeter is ideal for applications demanding precise measurements of phase or frequency, including precision metrology and heterodyne interferometry, channel characterization in communication networks, clock recovery and signal reconditioning for digital communication systems, and laser frequency stabilization.

LIQUID INSTRUMENTS

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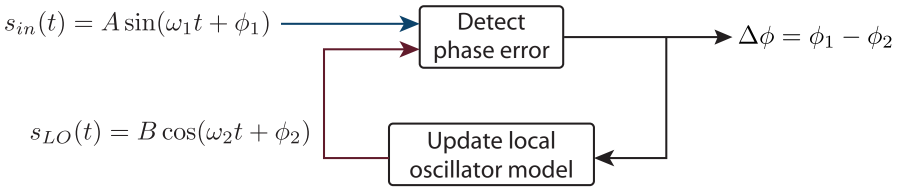
Introduction

How does it work?

Moku:Pro Phasemeter measures phase using a digitally implemented phase-locked loop, which uses feedback control to continuously update the phase of a local oscillator to equal that of the input signal.



The instantaneous phase error between the input signal and local oscillator is detected via demodulation using a digital multiplier and low-pass filter, almost identical in principle to a lock-in amplifier. The detected phase error is then passed through a PID controller to generate a feedback control signal to continuously update the phase of the local oscillator. The phase of the input signal relative to the local oscillator is measured by keeping a record of every change made to the phase of the local oscillator.

Why use the Phasemeter?

Digitally implemented phase-locked loops have extremely high dynamic range, allowing them to continuously measure phase over millions of cycles with a sensitivity of better than 6 microradians. This is particularly important for applications where the phase is expected to drift over many wavelengths within the measurement time, but still requires extremely high measurement precision.

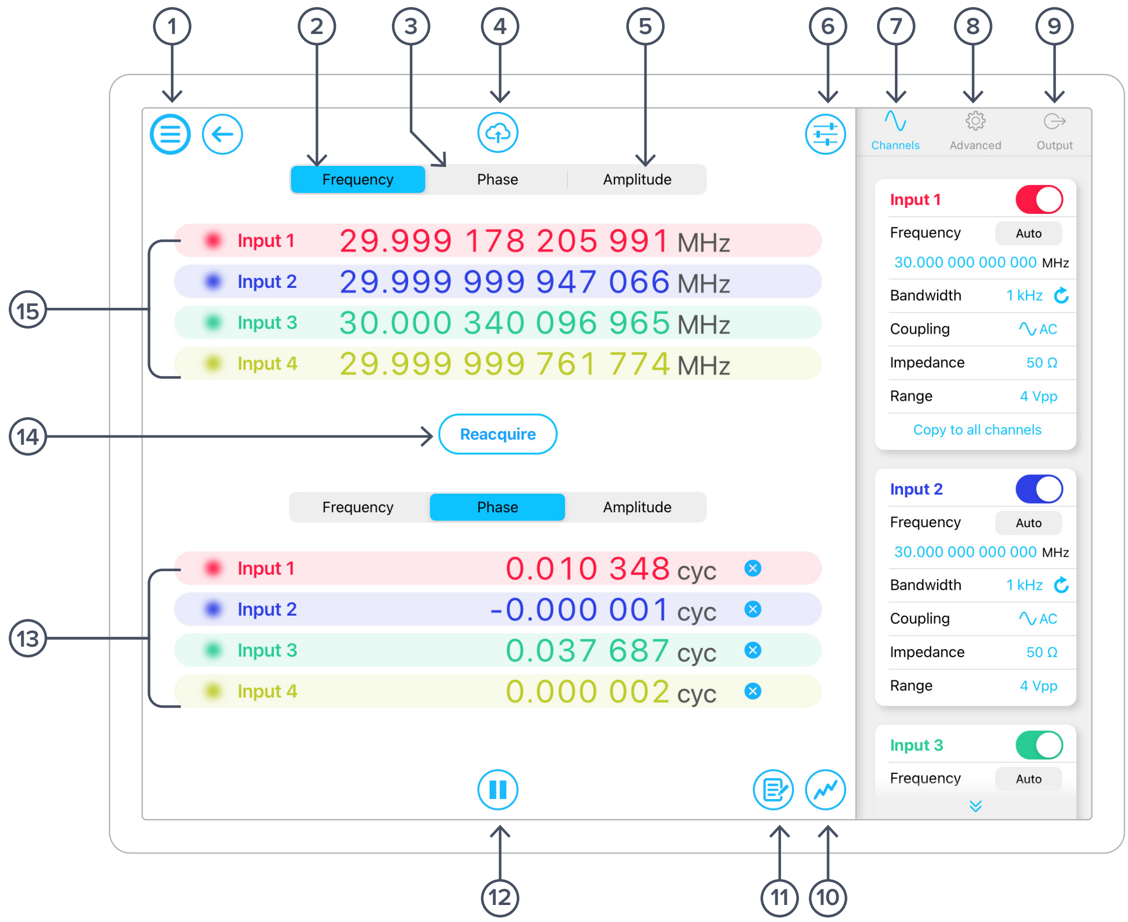
Heterodyne interferometry

One key application of phasemeters is in heterodyne interferometry, where displacement information is stored within the phase of a beat-note produced by interfering two electric fields with slightly different frequencies at a photodetector. Laser heterodyne interferometers are typically used to measure tiny displacements on the order of a fraction of the laser wavelength.

At a laser wavelength of 1064 nanometers, Moku:Pro Phasemeter can measure displacements with picometer sensitivity (i.e., one millionth of the wavelength of the laser). It is not uncommon, however, for heterodyne interferometers to experience displacements on the order of many thousands of wavelengths due to path-length contraction and expansion caused by shock, vibrations, and changes in temperature. And depending on their optical configuration, heterodyne interferometers can also be extremely susceptible to laser frequency noise, which typically appears as large, random excursions in phase at low frequencies.

The ability to measure phase with high dynamic range is therefore crucial in heterodyne interferometry.

User Interface



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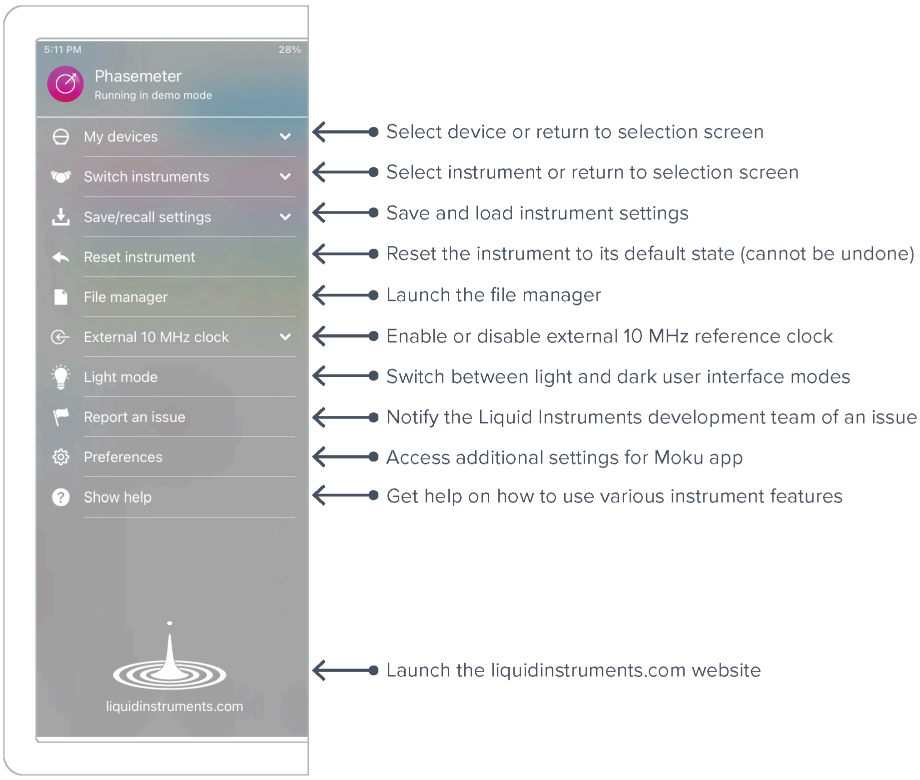
Main Menu

The **main menu** can be accessed by pressing the icon, allowing you to:



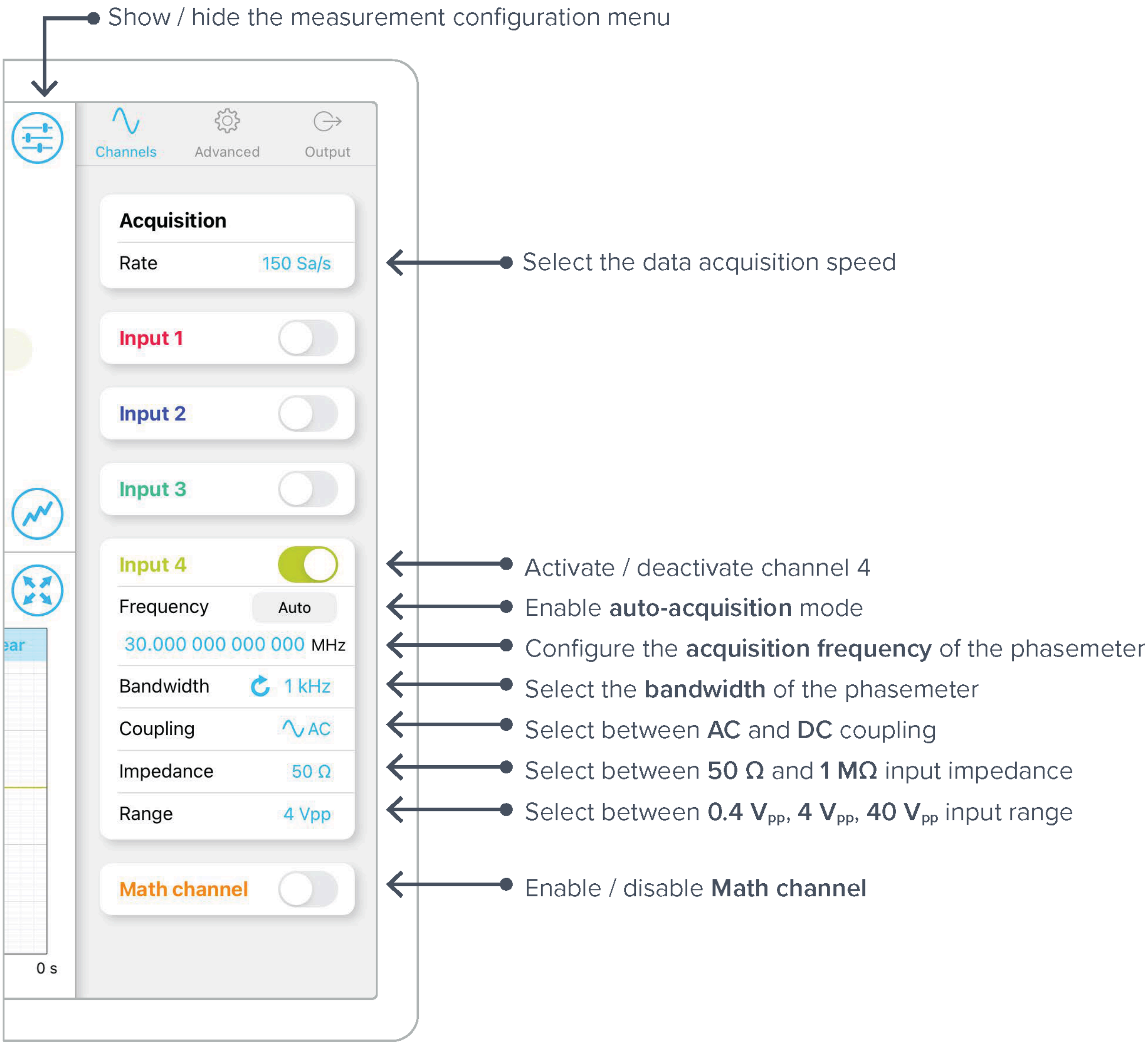
Instrument Configuration

The **configuration pane** allows you to configure the Phasemeter's channel settings and outputs.

Access the configuration menu by tapping the icon.

Moku:Pro is equipped with four input channels. You can swipe up and down to access different inputs. In this section, we will use input 4 as an example.

Channels



Acquisition frequency

- The Phasemeter will attempt to track frequencies around the specified acquisition frequency.
- If you know the frequency of the tone you want to measure, you can set it manually by tapping the blue number below the “Frequency” label.
- If you do not know the frequency of the tone you’d like to measure, you can enable auto-acquisition mode. This will automatically search for and track the highest-magnitude tone between 500 kHz and 300 MHz.

  Note: Auto-acquisition does not work reliably for tones below 500 kHz.

Bandwidth

- The Moku:Pro Phasemeter will reliably measure the phase of an input signal whose frequency varies at a rate up to the specified bandwidth.
- Select between 1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz bandwidth settings. **Note:** The selected bandwidth should not exceed one fifth of the acquisition frequency.

Input voltage range

- Select an appropriate input voltage range to avoid harmonic distortion caused by clipping.
- Input sensitivity is 10 times lower at $4V_{pp}$ input voltage range, and 100 times lower at $40V_{pp}$. If the amplitude of the input signal is lower than $400mV_{pp}$, use the $400mV_{pp}$ input voltage range setting.

Acquisition speed

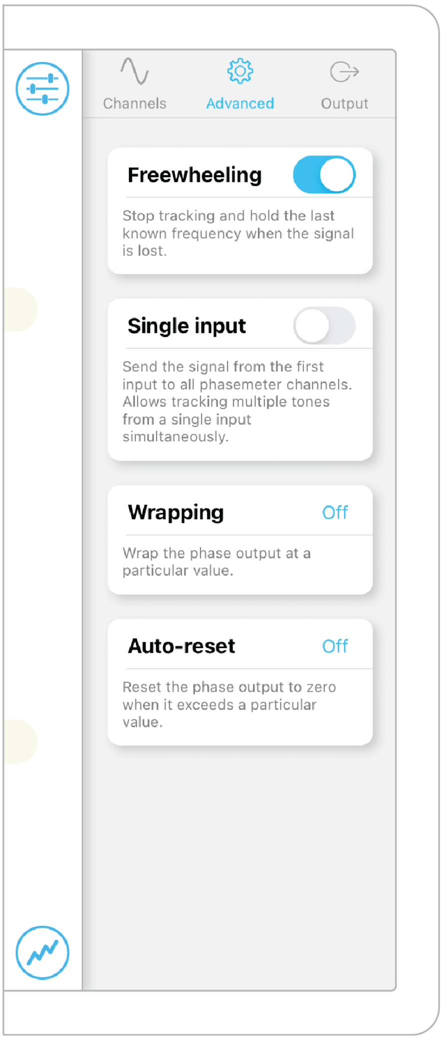
- Acquisition speed specifies the sampling rate at which phase, frequency, and amplitude data is saved to file or streamed over a network.

Math channel

- Use the Math channel to measure differences between any two input channels

Advanced

Use this pane to enable and configure advanced options.



Outputs

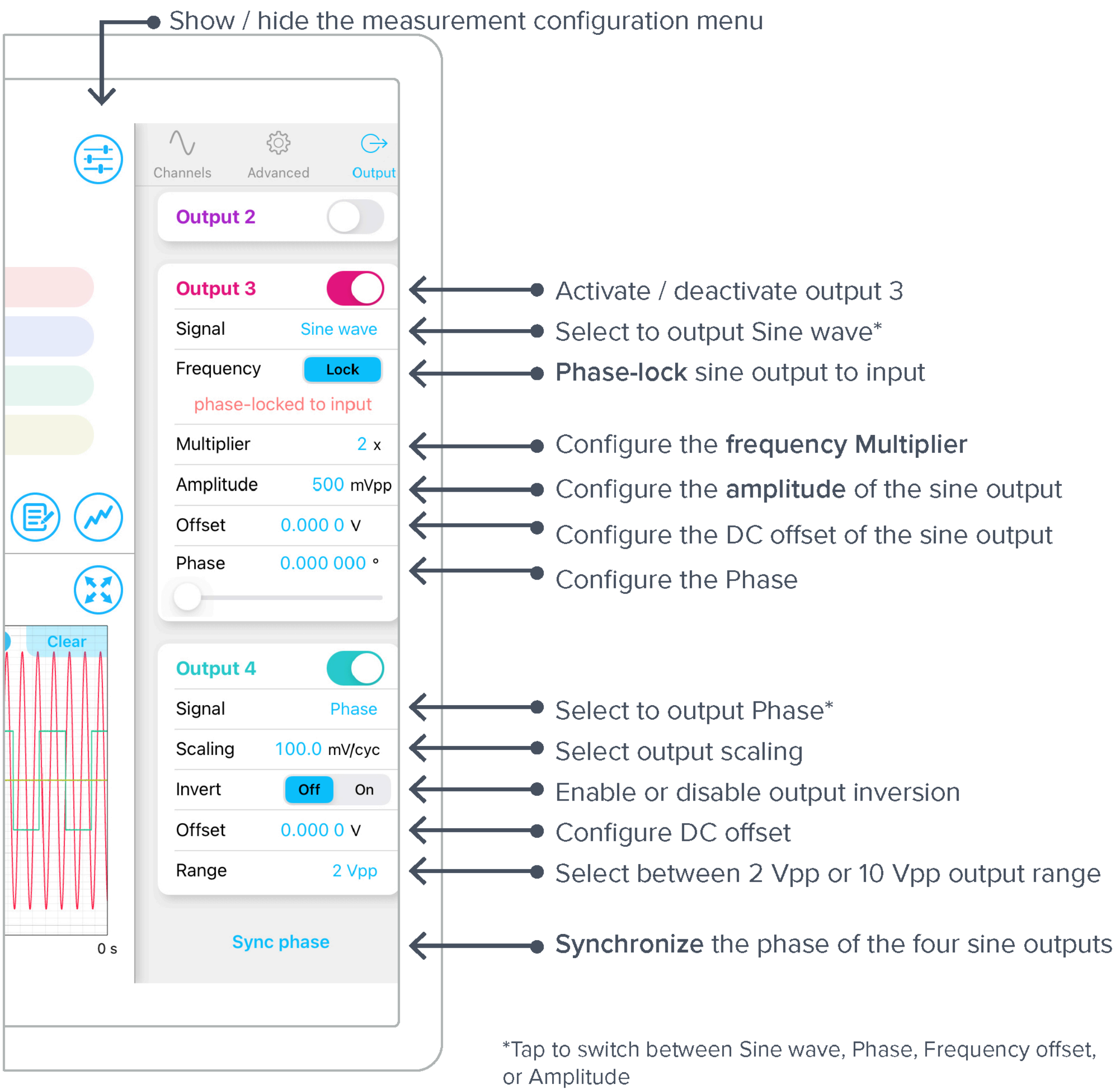
The Phasemeter features four sine generators with manual control over amplitude, frequency, and phase. The sine wave can be set to be phase-locked to their corresponding input channel. Using the Multiplier the signal can also be multiplied up to 250x or down to 1/8x.

Alternatively, the output can generate a voltage signal that is proportional to the accumulated phase error, frequency offset, or amplitude for closed-loop control applications.

The phase of all outputs can be synchronized by tapping the **Sync phase** button at the bottom of the tab.

Phase-locked output

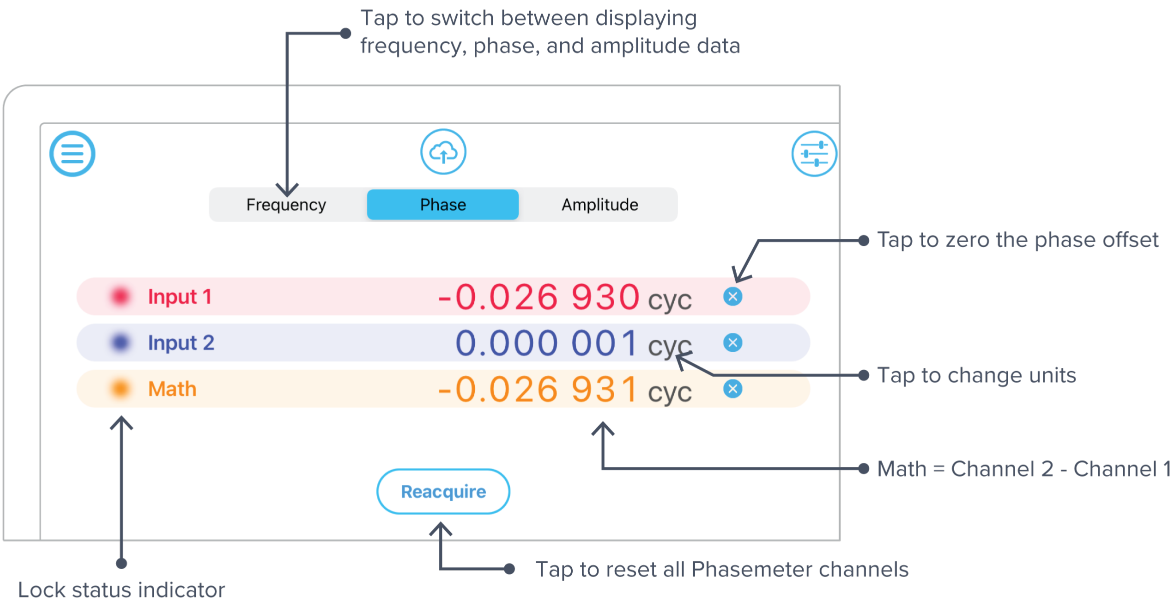
- Generate an output tone that is phase-locked to the input signal.
- Use the Multiplier to output the signal at up to 250x or down to 1/8x the input signal frequency. The minimum step size is 1/8x.
- The amplitude and phase of the generated tone remains configurable.



*Tap to switch between Sine wave, Phase, Frequency offset, or Amplitude

Measurement Data

Moku:Pro is equipped with four input channels. In this section, we will use channel 1, channel 2, and the math channel to demonstrate.



Measurement tabs

Frequency

- The frequency measurement tab displays the input signal's frequency in hertz (Hz).

Phase

- The phase measurement tab displays the input signal's phase in units of cycles (cyc), radians (rad) or degrees (deg).
- Tap the gray "units" text to switch between the available units.
- Zero the phase offset by tapping the ⓧ icon on the right side of the display. Zeroing the phase offset of the math channel will zero the phase offset between math channels.

Amplitude

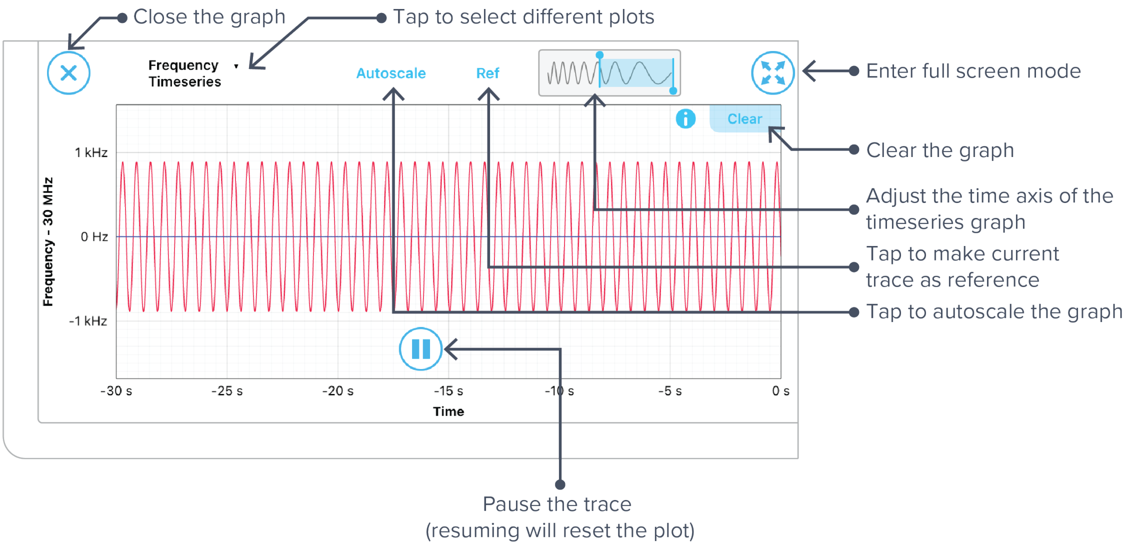
- The amplitude measurement tab displays the input signal's amplitude in units of volts RMS (V_{rms}), volts peak-to-peak (V_{pp}), or decibels (dB).
- Tap the gray "units" text to switch between the available units.

Reacquisition

- Tap the **Reacquire** button to reset both phasemeter channels simultaneously.
- All channels are reset at the same time to maintain synchronization.
- If a channel loses phase lock, the text on the corresponding row will be grayed out.

Data Visualization

The data visualization panel can be accessed by tapping the icon at the bottom right corner of the interface, allowing you to display measurement data for enabled channels in a variety of formats and over different time and frequency scales.



Plot Types

Frequency, phase, and amplitude data can be displayed in different formats, including time series, power spectral density, amplitude spectral density, coherence, Rayleigh spectrum, and Allan deviation. All plot types can be auto-scaled.

Time series

- Time series data can be viewed over time spans ranging from 0.5 seconds to 600 seconds.
- Adjust timescale and span using pinch gestures anywhere on the graph.
- Set the start and end times of the span manually using the slide rule located above the graph.

Power spectral density

- Power spectral density describes a signal's distribution of power at different frequencies.
- The units of power spectral density are proportional to amplitude^2/Hz (e.g., cycles^2/Hz).

Coherence

- Spectral coherence is a unitless statistic used to measure the similarity between two signals.

Amplitude spectral density

- Amplitude spectral density provides a measure of a signal's amplitude at different frequencies.
- The units of amplitude spectral density are proportional to amplitude/√Hz (e.g. cycles/√Hz).
- Amplitude spectral density is equal to the square root of the power spectral density.

Allan deviation

- Allan deviation is a unitless measure of stability, typically used to quantify the stability of clocks and other oscillators.
- Allan deviation is equal to the square root of the Allan variance.
- An Allan deviation of 2×10^{-6} at an averaging time of $\tau = 1$ seconds means there is an RMS error between two measurements one second apart of 2×10^{-6} cycles.

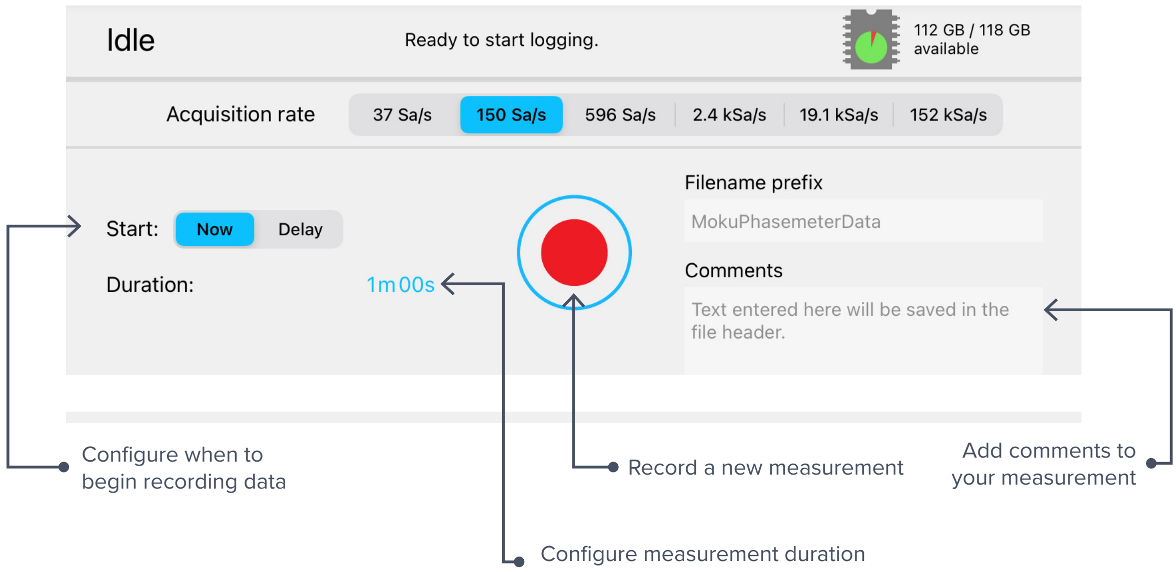
Rayleigh spectrum

- Rayleigh sprectrum is a measure of the coefficient of variation of the power spectral density
- A value of 1 indicates gaussian variation, less than one indicates coherent variation, more than one indicates incoherent variation

Data Acquisition

The Moku:Pro Phasemeter can acquire data at a maximum acquisition speed of 152kSa/s for all 4 channels. To access the data acquisition menu, press the icon.

- Data can be saved to the SSD as ***.li** file, or streamed over a network
- Files saved with binary *.li format can be converted to *.csv or *.mat using Liquid Instruments file conversion software.
- Record data for up to 10,000 hours and delay the start of a logging session for up to 240 hours.
- Tap / click the red circle to start a logging session.



Note: You cannot deploy a new instrument while there is an active logging session.

Data streaming

When configured through the Moku API, the Phasemeter can stream over a network, instead of saving directly to the device. More streaming information is in our API documents at apis.liquidinstruments.com.

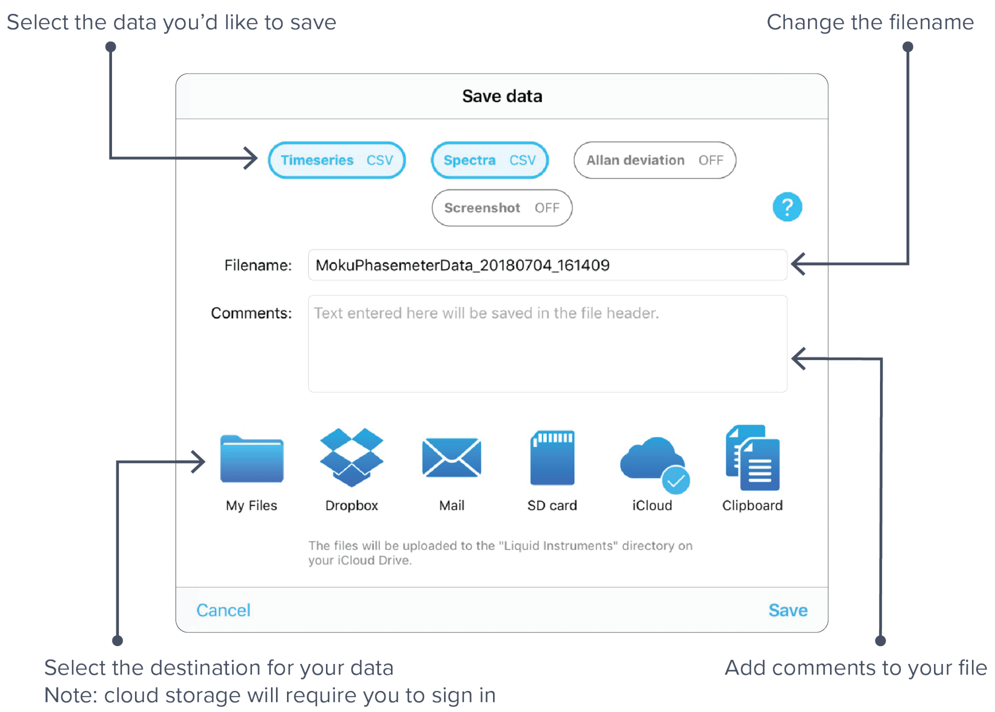
Exporting data

Export data by pressing the icon at the top of the interface.

Live Data

Measurement data can be uploaded to My Files (iOS 11 or later), Dropbox, email, iCloud, or Clipboard (screenshot is not copied to the clipboard).

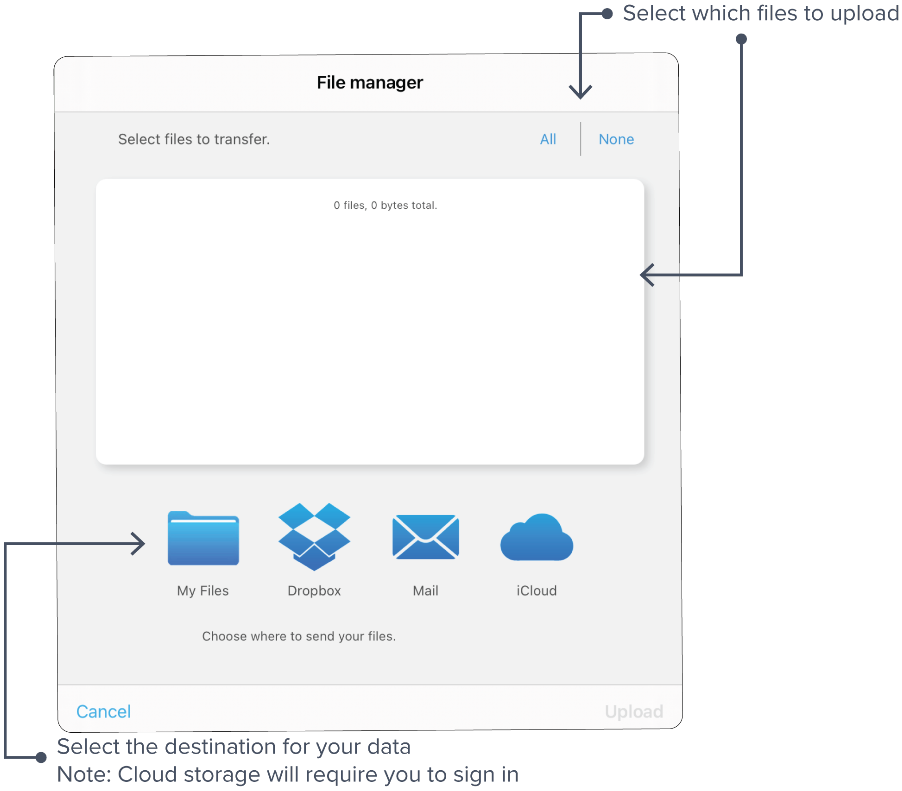
To export live data, tap the icon and select the "live data" option.



Logged data

Data that has been acquired to SSD storage can be uploaded to My Files (iOS 11 or later), Dropbox, email, and iCloud.

To export logged data, press the icon and select the "logged data" option.



Example Measurement Configurations

Measure the relative phase of two signals

To measure the phase of one signal with respect to another:

1. Connect the two signals to the Moku:Pro, input 1 and 2.
2. Enable the math channel and set it to measure the difference between input 1 and 2.
3. Configure the two input channels for your measurement setup.
    a. The acquisition speed and bandwidth settings limit the range of frequencies within which you can observe changes in magnitude and phase. For example, to observe features up to 200 Hz, set the bandwidth to be at least 600 Hz and the acquisition rate to be at least 488 Hz.

    Note: When measuring the relative frequency, phase, and amplitude of two signals, it's often useful to configure both channels identically to maximize the rejection of common sources of error and noise in the delta measurement.
4. When both channels have been configured, tap the **Reacquire** button to synchronously reset both phasemeter channels.
5. View the data in the frequency and time domains by tapping the icon. Double tap the graph to automatically scale the vertical axis, adjust the horizontal axis using the slider located above the graph or by using pinch gestures.

    Tip: Tap the "clear" button at the top right of the graph every time you reacquire to discard transient data which can sometimes corrupt the quality of the graph.
6. To record data, tap the icon and configure the data logger as required for the measurement.

Note: If the Moku:Pro internal clock is not synchronized to that of the device generating the input signals, you can expect the measured phase for channels 1 and 2 to ramp linearly over time.

The reason this occurs is because phase is the integral of frequency, which means that any DC frequency error between the internal clock and that of the external source will cause the measured phase to grow at a rate proportional to the frequency difference between the two devices.

If the two input signals are generated by the same source, the frequency error will be common to both phase measurements and will be canceled out in the delta phase measurement.

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