Moku Laser Lock Box

User Manual

LIQUID INSTRUMENTS

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Introduction

The Laser Lock Box instrument is a powerful tool for implementing feedback-controlled laser frequency stabilization. Laser locking systems are widely used to control and match a laser's frequency to a reference, such as an optical cavity, atomic transition, or another laser. Such systems are vital for precise interferometric measurements, spectroscopy, and frequency standards. Locking a laser forces the laser frequency to match the reference and allows for two scenarios:

- Frequency stabilization, where the locking system corrects any drifts of the laser frequency away from the reference, and:
- Frequency tracking, where the locking system steers the laser frequency to follow the reference.

The Moku Laser Lock Box is designed for high-performance in both laser frequency stabilization and frequency tracking applications. It offers advanced setup, acquisition, and diagnostic features that make it easier and quicker to set up and characterize laser locking systems. The Laser Lock Box incorporates staged locking and a "Lock Assist", enabling a user-defined locking process to quickly lock to any zero-crossing on the demodulated error signal. It also features an embedded Oscilloscope, allowing you to observe signals at any point in the signal processing chain at up to 5 GSa/s, and a built-in Data Logger for long-term recording of signals.

These user manuals are tailored to the graphical interfaces available on macOS, Windows, iPadOS, and visionOS. If you'd prefer to automate your application, you can use the Moku API; available for Python, MATLAB, and LabVIEW, refer to the API Reference.

AI-powered help is available to aid both workflows. AI help is built into the Moku application, and provides fast, intelligent answers to your questions, whether you're configuring instruments or troubleshooting setups. It draws from Moku manuals, the Liquid Instruments Knowledge Base, and more, so you can skip the datasheets and get straight to the solution.

Access AI help from the main menu

For more information on the specifications for each Moku hardware, please refer to our Product Documentation, where you can find the Specifications and the Laser Lock Box Datasheets.

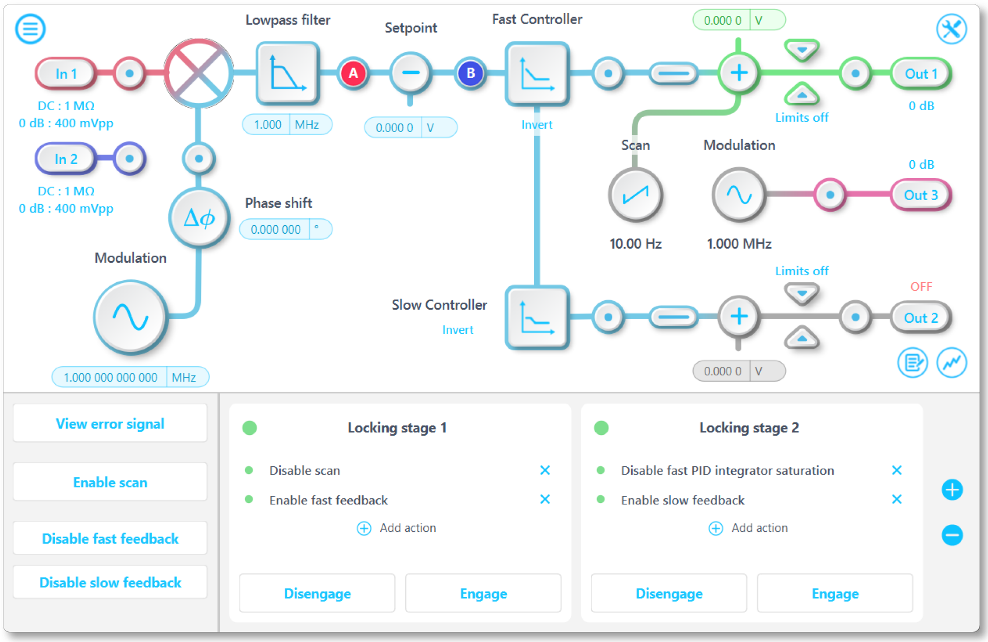


Figure 1. Laser Lock Box user interface showing its block diagram control panel (top) and locking stages interface (bottom).

Quick start guide

Here we outline how to set up the Moku Laser Lock Box and highlight a typical use case for the instrument, laser stabilization. Further, more detailed, examples may be found in the Examples section.

The guide below is based on Pound-Drever-Hall stabilization technique in which a laser is stabilized to an optical cavity. In this example, a Coherent Mephisto S fiber laser (1064 nm) is modulated by an electro-optical modulator (EOM) and redirected into an optical cavity. Two photodetectors (PDs) are placed to detect the transmitted and reflected light from the cavity. The signals detected on the PDs are fed into Moku Input 1 for the reflected signal (error signal) and Input 2 for the transmitted signal (monitor signal). Output 1 of the Fast controller is then connected directly to the laser's piezo to actuate laser frequency, and Output 2 of the Slow controller is connected to the temperature control of the laser. Output 3 from Moku provides the modulation signal to the EOM.

Note: For Moku:Lab and Moku:Go, the Laser Lock Box can be used with a bias tee. This would allow split the oscillator signal for EOM and actuator signal for PZT. Moku:Pro and Moku:Delta allows all three to be generated separately.

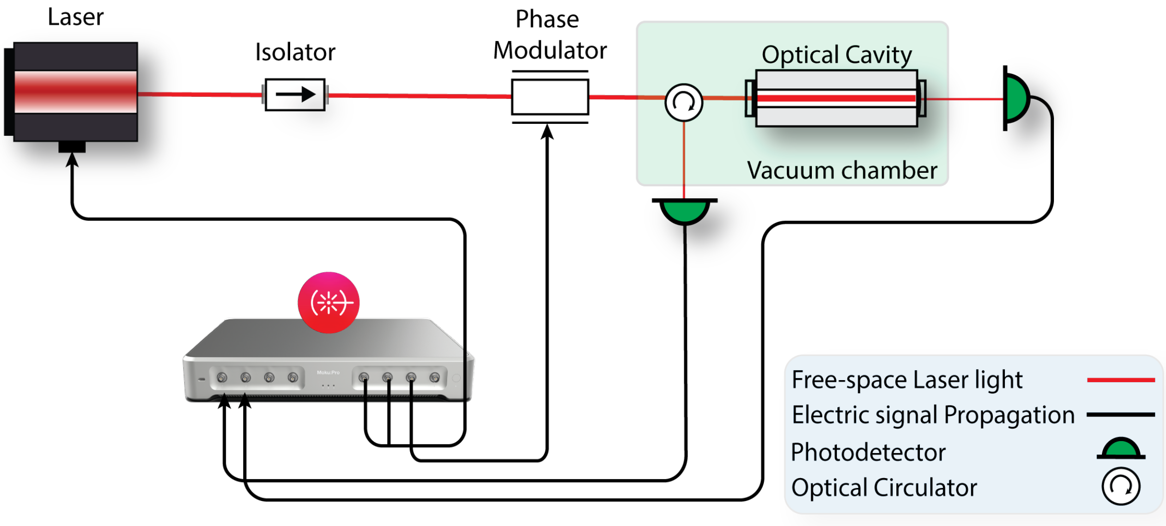


Figure 2. Experimental setup illustrating PDH technique.

Step 1: Configure the Demodulation source

- Select the Demodulation source as Modulation. This will ensure the demodulation frequency matches the modulation frequency that is generated and connected to the EOM.

Step 2: Enable the Modulation

- Select the Modulation signal and set the frequency to a value much larger than the cavity linewidth and set the amplitude with regards to V_{pi} of the phase modulator (EOM) and enable the output. The frequency is set to 1 MHz, much higher than the cavity linewidth of 10 kHz. The amplitude is set to 800 mVpp to have optimal PDH performance at a modulation depth of 1.08 rad.

Step 3 Finding the error signal or cavity resonance.

- Select "View error signal" and select the to enable the Lock Assist mode. This will open the embedded Oscilloscope and put a Probe after the demodulation step. At the same time, the output will generate a Scan signal that can be used to sweep the laser frequency to find the cavity resonance. To ensure a strong error signal is achieved, optimize the following parameters:
  - Put probes on In 1 (and optionally In 2) to observe the cavity resonance condition using the reflected signal while sweeping the laser frequency. If the signal has any saturation on In 1, change the attenuation and gain settings to accommodate the signal.
  - By default, the Scan signal is connected to the Out 1 (piezo actuator) with a 500 mVpp triangular signal at a frequency of 10 Hz. If the cavity resonance is not within the PZT range, then enable Out 2 (thermal actuator) and adjust the output offset till the cavity resonance can be observed. *Note that the Scan signal can also be passed to Out 2 (the thermal actuator), however a low frequency (<10 mHz) should be maintained to provide enough time to observe the cavity resonance.*
  - After the resonance condition is found, view the PDH error signal again. Vary the Phase Shift to change the PDH error shape. Set the phase to obtain the maximum error slope.
  - If the PDH error signal is too noisy, use the Lowpass filter to filter out the noise. Reducing the cut-off frequency can improve signal visibility and make it easier to achieve the initial lock. Alternatively, use Precision Mode in the Oscilloscope for better visibility. Here we use a 100 kHz low-pass filter cut-off. *Note: Changing the Lowpass filter settings can affect the open loop response of your feedback system. After initial lock acquisition, you can revert back to a higher cut-off frequency for larger control bandwidth.*

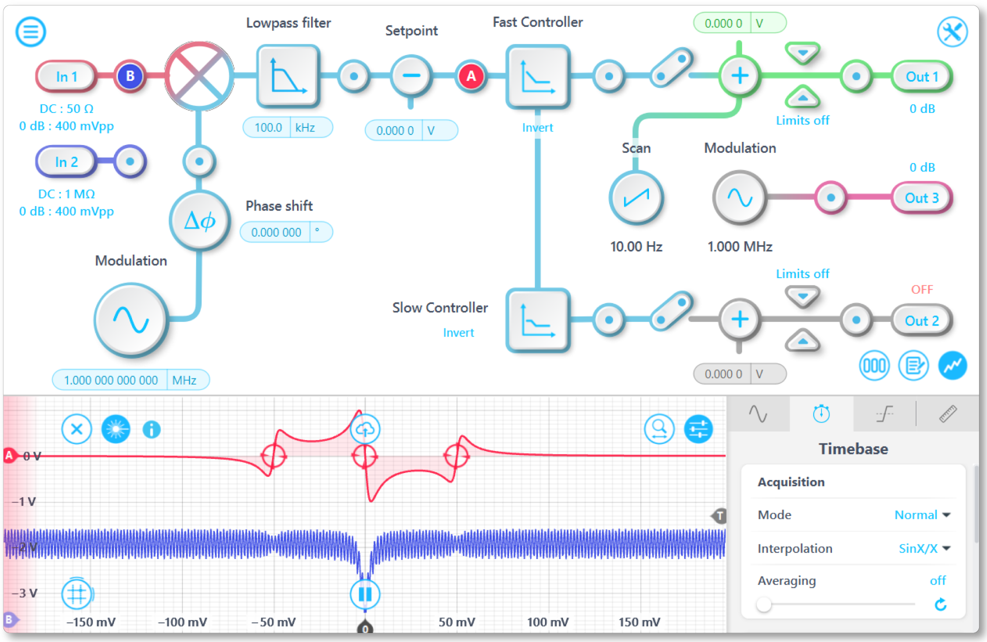


Figure 3. Enabling the Scan signal and using Lock Assist mode to find zero-crossing point.

Step 4: Set the Fast controller and enable the lock

- After obtaining a valid PDH error signal, ensure that the Fast controller is configured with low gain and saturation for easier lock acquisition. Here, the Proportional gain is set to 0 dB and the Integrator is set to 1 kHz with Integrator saturation level at +20 dB.
- If the laser actuators are rated below Moku's output voltage range, ensure the voltage limits are applied as appropriate.

- In the Oscilloscope, the Lock Assist will still be enabled, with the PDH error having crosshairs on the zero-crossing points. This zero-crossing point can be varied by changing the setpoint. Enable the control loop by pressing on the middle cross-hair of the PDH error signal. This will close the output switch and disable the Scan.

Step 5: Disabling the Integrator saturation and tuning the controller

- Enable the probe on Out 1 and observe the output signal. On the PID Controller, disable the Integrator saturation. If the output signal reaches the voltage limits, re-enable the saturation and lower the Integrator gain. Test the lock acquisition by enabling the Lock assist again. Repeat the steps until a stable lock is achieved. A similar approach would be to start with a very low gain and gradually increase it, assuming the system allows for the desired PID response in steady state. *Note: Verify theoretically that the open loop response is stable for desired PID configuration. An unstable controller setup would never work in the feedback system.*

Step 6: Enabling the Slow controller

- Enable Output 2 (if thermal offset is not used already) and set the Slow controller to a low gain integrator. Close the Slow controller switch and observe the signals in Out 1 and Out 2. The Out 1 should now center around zero, maintained by the output from the Slow controller. If the slow output causes Out 1 to reach the voltage limits, open the switches to the Fast and Slow controller, and repeat steps 4-6, reducing or inverting the Slow controller output.

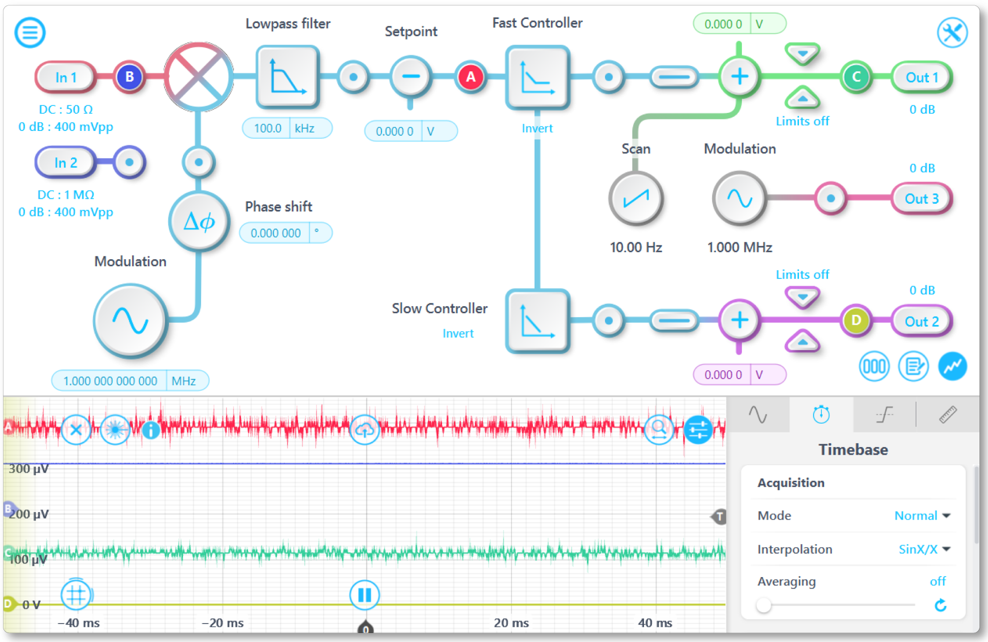


Figure 4. Observing the error and actuator signals after closing the feedback loop.

Step 7: Logging the error and control signal

- Once the lock is maintained, use the probes to observe the error signal and the actuator signal(s). To monitor the lock behavior over long periods, we can utilize the embedded Data Logger. Click on to open the logger interface. Set the sampling rate to the desired rate, 100 Sa/s in this example, and a duration of 10 hours. Start the logging session and export it later to observe the data. If the lock is still intact, then the data will provide details on how the thermal and PZT actuators have drifted over time.

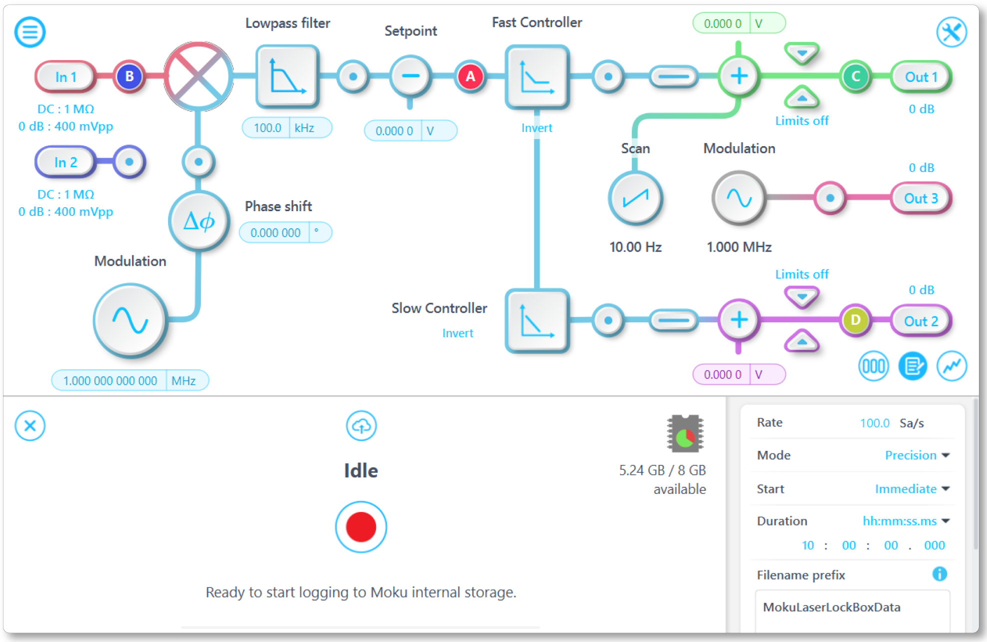


Figure 5. User interface of the Laser Lock Box to log the selected probe points.

Principles of operation

The Laser Lock Box is a digital implementation of the electronics used in typical laser locking experiments, with many demodulation options to best suit your application and locking technique. It replaces multiple separate components with a single, easy-to-use device, reducing distortion and insertion loss and simplifying the locking process. The default block diagram displays the signal flow in Pound-Drever-Hall laser stabilization, in which a laser is locked to a reference optical cavity. The computations involved in the setup follow a path from error detection to control for the feedback system.

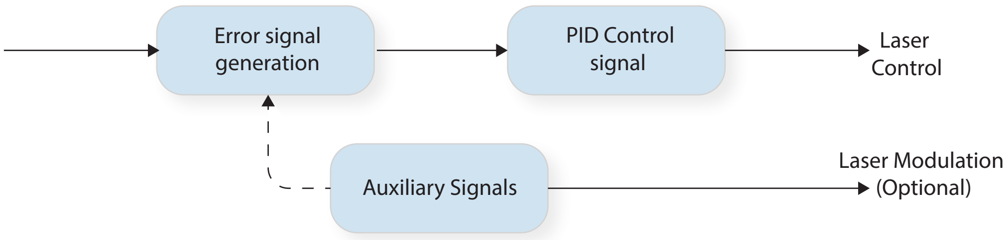


Figure 6. Schematic of the Laser Lock Box.

The Laser Lock Box can be divided into two parts: a sensing block and a PID Controller block. The sensing block computes the error signal deviations for the controller to correct. The PID controller scales the measured error to an appropriate signal for the actuator. The actuator in turn controls the laser feature (either phase, frequency, or intensity).

The sensing block can be realized through a demodulator block with an internal or external reference signal, or through an external mechanism that generates the error signal. The signal can then be filtered to generate the error signal for control. In a PDH setup, the error signal is synchronized with the phase modulation signal, which is also generated by Moku and passed to the EOM.

The PID controller operates at two sampling rates, named the fast and slow controllers. This would correspond to two actuators in commercial lasers which are controlled by PZT and thermal actuators. Other actuators include Electro-Optic Modulator (EOM) and Acoustic-Optic Modulator (AOM) that vary the phase and frequency of the laser light, or Voltage Optical Attenuator that can change the intensity of the laser.

The Laser Lock Box also features Lock Assist to make it easier to lock onto one of the zero crossings of the error signal. Enabling Lock Assist will configure the Oscilloscope so that it synchronizes with the scan waveform. Scrolling and zooming horizontally on the graph will then adjust the scan offset and amplitude instead of the Oscilloscope time base. Selecting one of the zero-crossings in the error signal will then adjust the output offset to the corresponding voltage and engage the next Locking stage. These "Locking stages" can be configurable to enable/disable multiple elements (such as your Scan, feedback, PID Integrator, etc.) instantaneously.

For more information on PDH locking, please refer to this Application note.

Using the instrument

Signal inputs

The analog inputs to the Laser Lock Box allow you to change the analog frontend settings for each input. Tap the  icon to configure the input settings for the signal input.

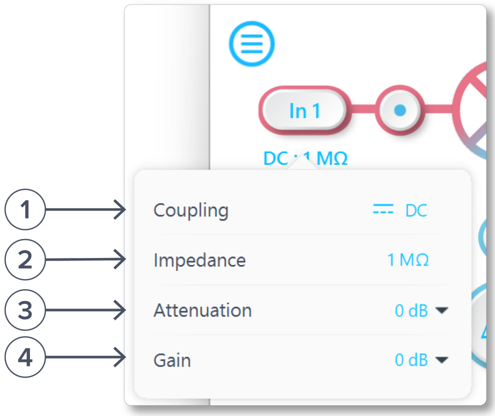


Figure 7. Signal Inputs.

ID	Description
①	Select between AC and DC input coupling.
②	Select between 50 Ω and 1 MΩ input impedance (hardware dependent)
③	Select an input attenuation between 0 dB and -40 dB (hardware dependent).
④	Select an input gain between 0 dB and +48 dB (hardware dependent). *Note: This option is only for Input 1.*

Demodulation settings

Demodulation source

You can rapidly reconfigure Laser Lock Box digital signal processing layout to suit different applications. Access the advanced configuration menu using the icon at the top right of the interface. Select between Modulation, Internal, External (straight-through), or External (PLL) as a phase-locked demodulation reference. Alternatively, you can bypass the demodulation by selecting None.

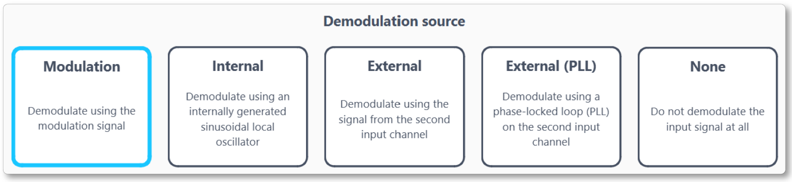


Figure 8. Instrument Configuration options.

- **Modulation:** The Modulation option allows the use of the same internal oscillator signal as the output. Changing the frequency on the demodulation/modulation would change both settings simultaneously.
- **Internal:** The Internal option allows the use of the local oscillator within the Moku, while simultaneously generating a different oscillator signal for the output. Both oscillators utilize the same timebase as that of the Moku's clock reference. *Note: Moku devices with external clock reference ports can use the timebase from an externally connected device.*
- **External (Direct):** The External option allows the second input channel to be used as the reference oscillator. This allows the use of non-sinusoidal demodulation and can be used to measure correlation or recover specific components of complex input signals.
- **External (PLL):** The External (PLL) option also allows the second input channel to be used as the reference oscillator. This option uses a digitally implemented phase-locked loop (PLL) to track the phase of the external reference within a user-selectable bandwidth and generate a phase-locked copy. The PLL will automatically lock to the strongest harmonic of the external reference within the device's range in Auto mode, or you can manually enter the frequency to be tracked. Use the reacquire button to re-lock to the external reference. The PLL multiplier lets you generate harmonics of the external frequency from the 8th subharmonic up to the 250th harmonic, in steps of 0.125x, within the device’s bandwidth limits.
- **None:** The None option can be used to bypass the mixing operation, passing the signal directly to the input. This is useful if the necessary signal extraction is done on an external system or another instrument in Multi-Instrument Mode and enables modulation-free locking techniques such as DC locking, side of fringe locking, and tilt locking.

Filter

After the mixer, a filter can be used to remove frequency content. These filters can be configured to be either Lowpass filter, Bandstop filter or a Custom filter. The filters are made of 2 second-order system (SOS) filters whose coefficients are set by the cut-off frequencies and gains.

Lowpass: In the Laser Lock Box, the Lowpass filter consists of two cascaded SOS filters. You can switch the filter order between 2 and 4. Increasing the order of the cascaded filters increases the "roll off" angle of the slope and improves stop-band rejection. The low-pass filter can be set by its corner frequency f_c . The filter types available are Butterworth, Chebyshev I, Chebyshev II, Elliptic, Cascaded, Bessel, Gaussian and Legendre. For Chebyshev I and Elliptic filters, adjust the passband ripple; for Chebyshev II and Elliptic filters, adjust the stopband attenuation.

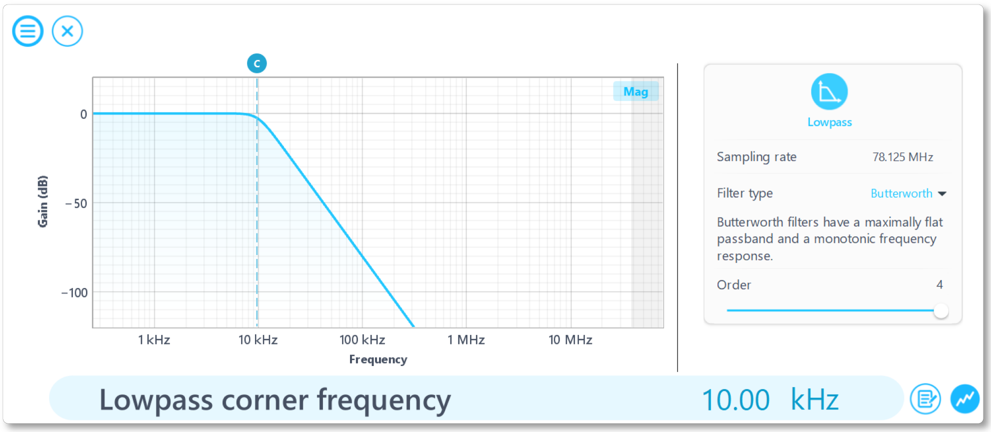


Figure 9. Low-pass filter option in Laser Lock Box.

Bandstop: The Bandstop filter is a fixed second-order filter that can attenuate certain frequency bands. This filter can be configured by setting the lower and higher cut-off frequencies. The filter types available are Butterworth, Chebyshev I, Chebyshev II, Elliptic, Cascaded, Bessel, Gaussian and Legendre. For Chebyshev I and Elliptic filters, adjust the passband ripple; for Chebyshev II and Elliptic filters, adjust the stopband attenuation.

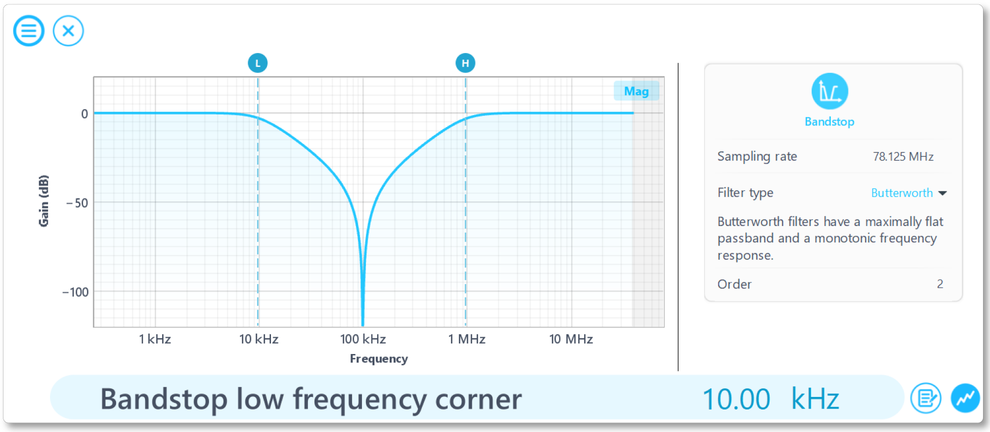


Figure 10. Bandpass filter option in Laser Lock Box.

Custom: The Custom filter options allow users to create their own filters to be used after demodulation. Users can upload coefficients of the SOS filters (up to 2 stages) to realize at most a fourth-order filter. The custom filter can be described using the below equation.

$$H(z) = g\prod_{k=1}^{2}\frac{s_k(b_{0k} + b_{1k}z^{-1} + b_{2k}z^{-2})}{1 + a_{1k}z^{-1} + a_{2k}z^{-2}}$$

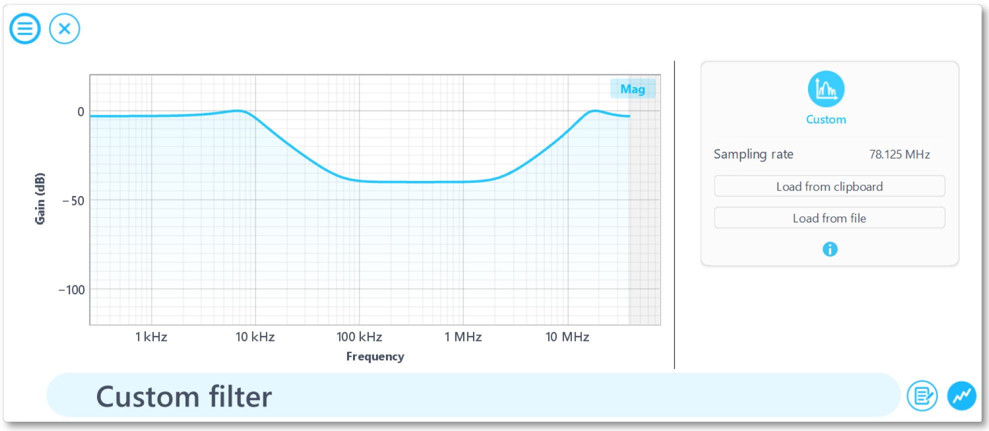


Figure 11. Custom filter option in Laser Lock Box.

These coefficients can be uploaded directly from a clipboard or from file.

Controller settings

Setpoint

The Setpoint adds a DC offset to the error signal after the Lowpass filter. The DC offset can be used to set the error point for a desired offset level which can then be used as the PDH error signal.

Fast controller

The Fast Controller is based on a PID Controller as detailed here. This Fast Controller operates at the largest sampling rate possible for the hardware device.

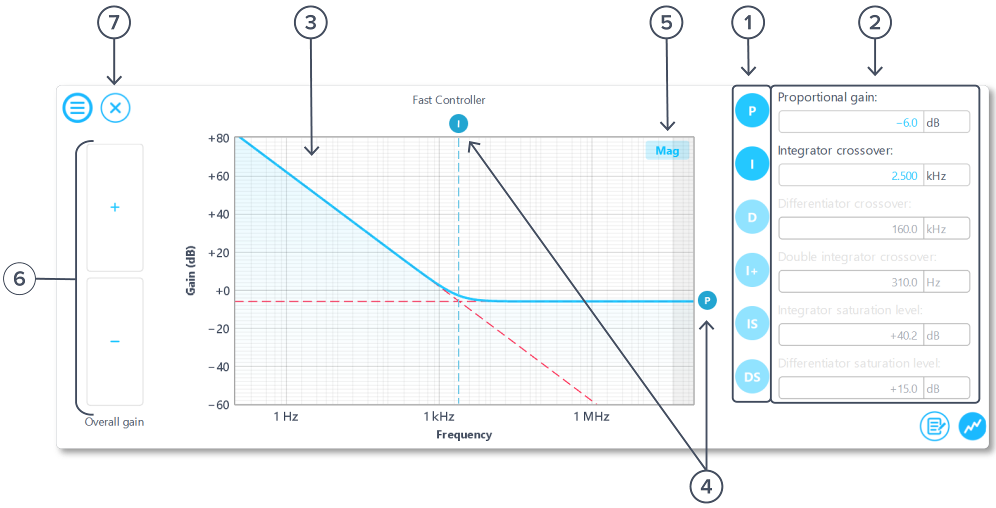


Figure 12. Block diagram of the Fast Controller in LLB.

① Enable/Disable button for the corresponding gain parameter.

② Field to observe or type in the numbers for each gain parameter.

③ Corresponding interactive PID response plot.

④ Markers on the plot indicate the enabled gain parameters.

⑤ Toggle between magnitude and phase graphs.

⑥ Increase/Decrease the Overall gain of the PID Controller.

⑦ Close the PID block.

The gain fields of the different parameters are described as below:

Table 1. Parameters of the fast PID block

Parameter	Description
Proportional gain [dB]	Adjust the Proportional gain of the PID Controller.
Integrator crossover/ unity gain frequency [Hz]	Adjust the Integrator gain. If the Proportional gain is enabled, the gain changes the crossover frequency, otherwise the Integrator gain changes its unity gain frequency.

Parameter	Description
Differentiator crossover/unity gain frequency [Hz]	Adjust the Differentiator gain. If the Proportional gain is enabled, the gain changes the crossover frequency, otherwise the Differentiator gain changes its unity gain frequency.
Double integrator crossover [Hz]	Adjust the Double integrator crossover with the Integrator. Note that the Double integrator can only operate with the Integrator enabled. The crossover of the Double integrator is less than or equal to the Integrator crossover/unity gain frequency.
Integrator saturation level [dB]	Adjust the saturation level on the Integrators (both Single and Double Integrators) at low frequencies. Note that the Integrator saturation can only operate with the Integrator enabled. The Integrator saturation level cannot be below the Proportional gain level.
Differentiator saturation level [dB]	Adjust the saturation level on the Differentiator at high frequencies. Note that the Differentiator saturation can only operate with the Differentiator enabled. The Differentiator saturation level cannot be below the Proportional gain level.
Overall gain [dB and/or Hz in other parameters]	Adjust the overall gain of the PID Controller. The Overall gain applies the effect to all paths of the PID Controller at the same time. If any of the paths hit the maximum or minimum allowable limits, the Overall gain adjusts the other paths.

Slow controller

The Slow Controller is based on a PID Controller as detailed here. Compared to the Fast Controller, the Slow Controller operates at 1/64th of the sampling rate, allowing for implementation of low-gain integrators and differentiators in the PID block. The reduced sampling rates would allow for implementing low-gain integrators and differentiators in the PID block.

The Slow Controller implements the PID block on the output of the Fast Controller. This means that the output from the Slow Controller path is a product of the cascaded effects of both the Fast and Slow Controller.

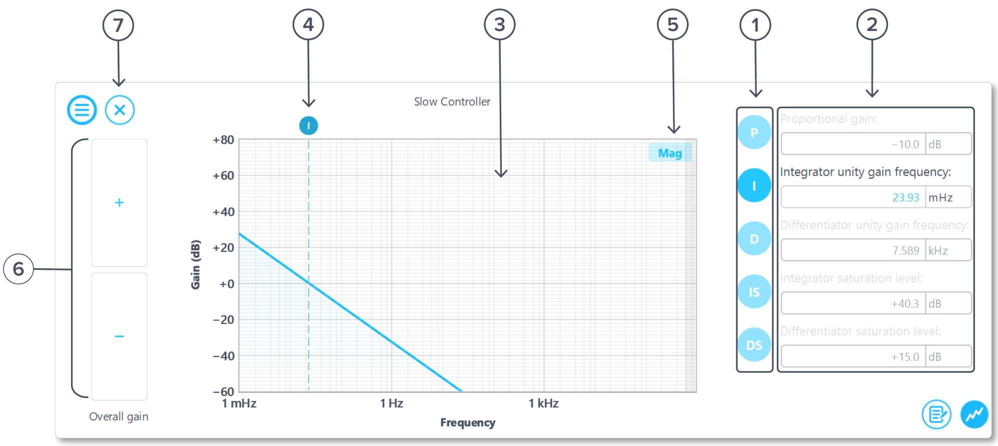


Figure 13. Block diagram of the Slow Controller in LLB.

① Enable/Disable button for the corresponding gain parameter.

② Field to observe or type in the numbers for each gain parameter.

③ Corresponding interactive PID response plot.

④ Markers on the plot indicate the enabled gain parameters.

⑤ Toggle between magnitude and phase graphs.

⑥ Increase/Decrease the Overall gain of the PID Controller.

⑦ Close the PID block.

The gain fields of the different parameters are described as below:

Table 2. Parameters of the slow PID block

Parameter	Description
Proportional gain [dB]	Adjust the Proportional gain of the PID Controller.
Integrator crossover/unity gain frequency [Hz]	Adjust the Integrator gain. If the Proportional gain is enabled, the gain changes the crossover frequency, otherwise the Integrator gain changes its unity gain frequency.
Differentiator crossover/unity gain frequency [Hz]	Adjust the Differentiator gain. If the Proportional gain is enabled, the gain changes the crossover frequency, otherwise the Differentiator gain changes its unity gain frequency.
Integrator saturation level [dB]	Adjust the saturation level on the Integrators (both Single and Double Integrators) at low frequencies. Note that the Integrator saturation can only operate with the Integrator enabled. The Integrator saturation level cannot be below the Proportional gain level.
Differentiator saturation level [dB]	Adjust the saturation level on the Differentiator at high frequencies. Note that the Differentiator saturation can only operate with the Differentiator enabled. The Differentiator saturation level cannot be below the Proportional gain level.
Overall gain [dB and/or Hz in other parameters]	Adjust the overall gain of the PID Controller. The Overall gain applies the effect to all paths of the PID Controller at the same time. If any of the paths hit the maximum or minimum allowable limits, the Overall gain adjusts the other paths.

Output conditioning

Outputs from controllers

Additional features in the Laser Lock Box includes switches to enable/disable the signal to the outputs, offsets and inverters for the control signal, and limiters on the output channels.

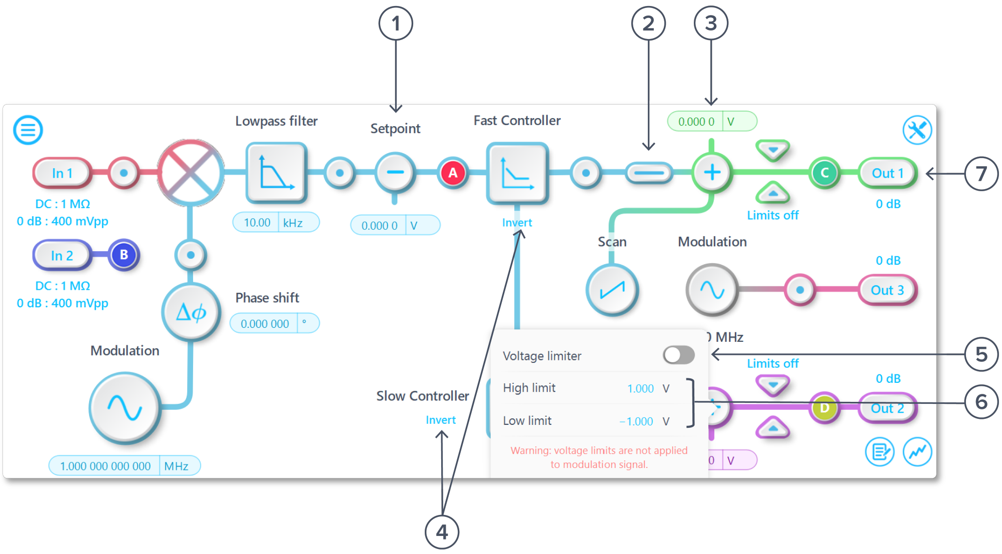


Figure 14. PID Input and Output Path settings.

① Type in the Setpoint offset for error signal computation.

② Open/close the output switch from controller to the output.

③ Type in the output offset before being generated as output.

④ Toggle to invert the control output.

⑤ Enable/Disable the Voltage limiter.

⑥ Type in the high and low voltage limits.

⑦ Enable/Disable the output and adjust the output gain (if applicable).

The switches can be opened or closed. When the switches are open, the switch gives zeros to the output. On tapping the output switch and closing it, the controller signal is given to the output signal path. **Every time the switches are re-opened and closed, the Integrator and Differentiator registers in the Controllers are cleared.**

A DC offset can be applied to the signal in both the Fast Controller and Slow Controller. These offsets can be applied to ensure the appropriate signal is given to the actuator.

Depending on the feedback setup, the control signals can be inverted. The Invert option can be enabled/disabled on both the Fast and Slow Controller outputs.

Voltage limits can be applied before the signals are generated from the output ports. These limits ensure the output is maintained at these voltage levels whenever the signal crosses the specified threshold. For example, consider a system with an actuator that only works with positive voltages. The voltage limits would be useful to ensure that the minimum voltage is always greater than zero.

Outputs for modulation

The Modulation signal is an auxiliary output in the Laser Lock Box. If the Demodulation source is set to Modulation, both will utilize the same internally generated oscillator. In typical setups such as cavity locking or spectroscopy systems, the Modulation signal can be used for phase or frequency modulation.

The modulation output is a sine generator whose amplitude and frequency can be varied. The modulation signal is added to either of the fast (Out 1) or slow (Out 2) outputs. On Moku:Pro and Moku:Delta, the modulation output can also be generated on a separate output channel (Out 3). *Note: The setup for combining the modulation signal with the control signal relies on the assumption that the modulation is much higher than the control bandwidth and can be split externally using a bias-tee.*

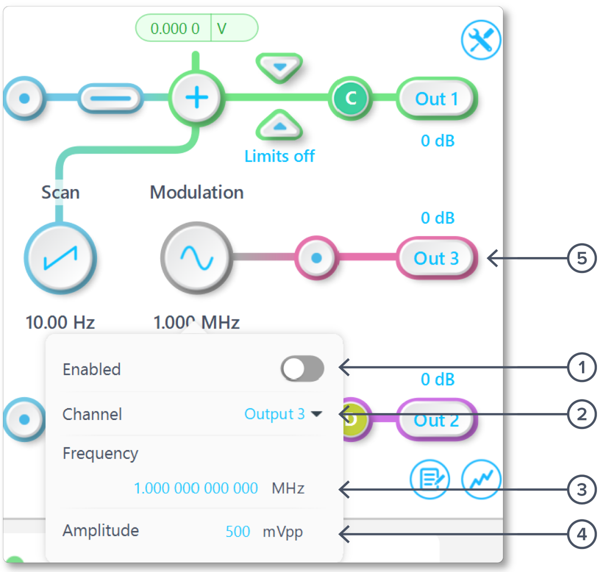


Figure 15. Modulation Output settings.

① Enable/Disable the Modulation signal.

② Select the channel to output the signal.

③ Type in the frequency of the sine wave.

④ Type in the amplitude of the sine wave.

⑤ Select the output gain between 0 dB, +14 dB (Only for Moku:Pro) or +20 dB (Only for Moku:Delta).

Observing the data

Embedded Oscilloscope

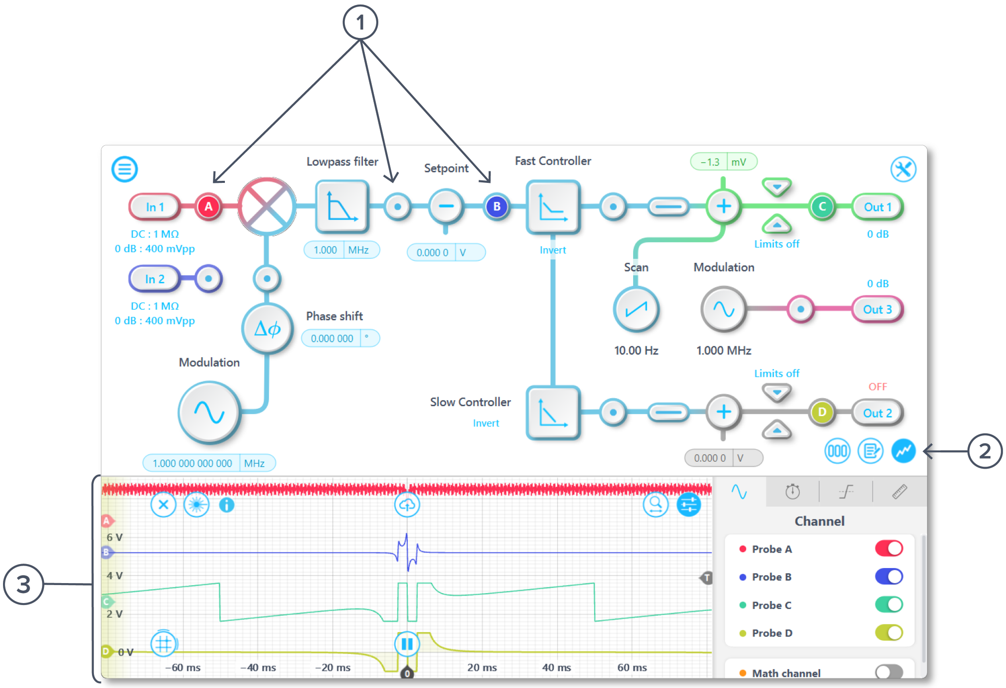


Figure 16. Probe points to view signals using the embedded Oscilloscope.

ID	Parameter	Description
①	Probe points	Click to place the probe point, the number available is device dependent.
②	Open embedded Oscilloscope and Data Logger	Click to open the embedded Oscilloscope or Data Logger .
③	Oscilloscope	Refer to the Oscilloscope user manual for the details.

Embedded Data Logger

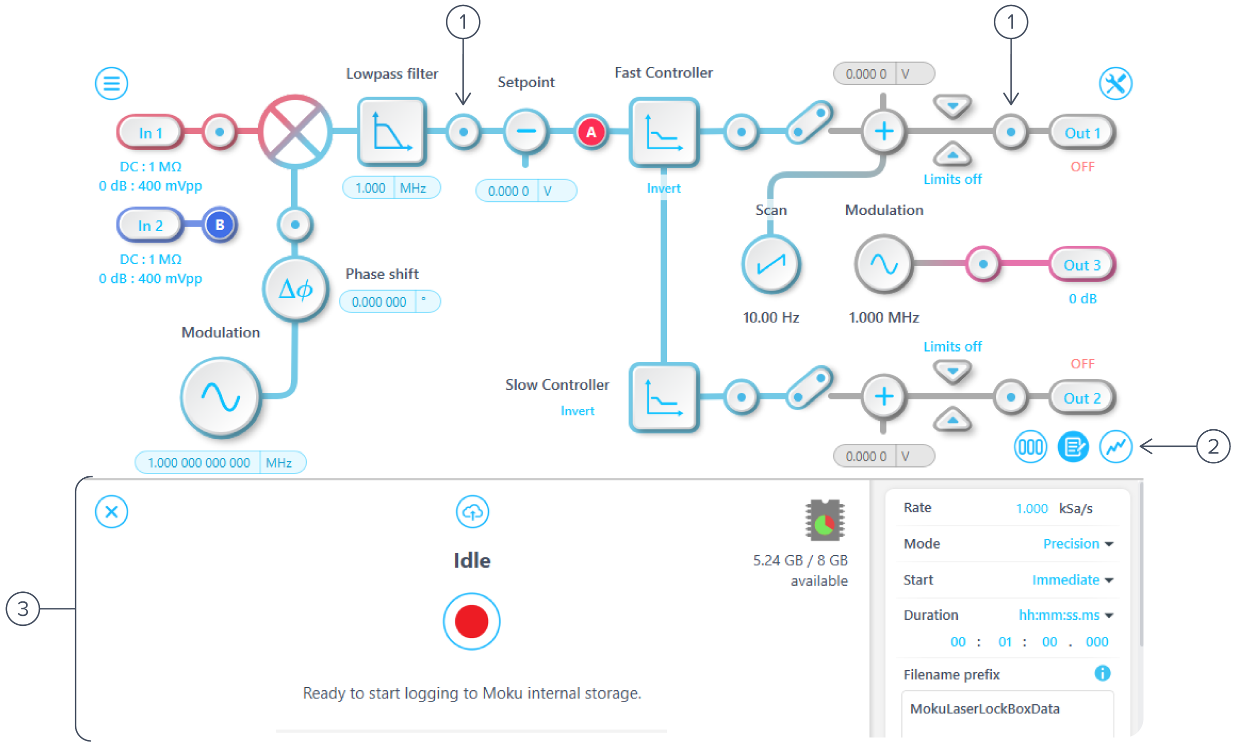


Figure 17. Embedded Data Logger in the Laser Lock Box.

ID	Parameter	Description
①	Probe points	Click to place the probe point, the number available is device dependent.
②	Open the locking stages, embedded Oscilloscope or Data Logger.	Open and close the embedded Oscilloscope, Data Logger, and locking stages.
③	Data Logger	Refer to the Data Logger user manual for the details.

The embedded Data Logger can stream over a network or save data to the onboard storage of your Moku. For details, refer to the Data Logger user manual. More streaming information is in our API Reference.

Exporting data

Export data by clicking the share icon . Any active probe points will be captured in the live data export or logging. Open the embedded Oscilloscope or Data Logger to export live and logged data, respectively.

Live data

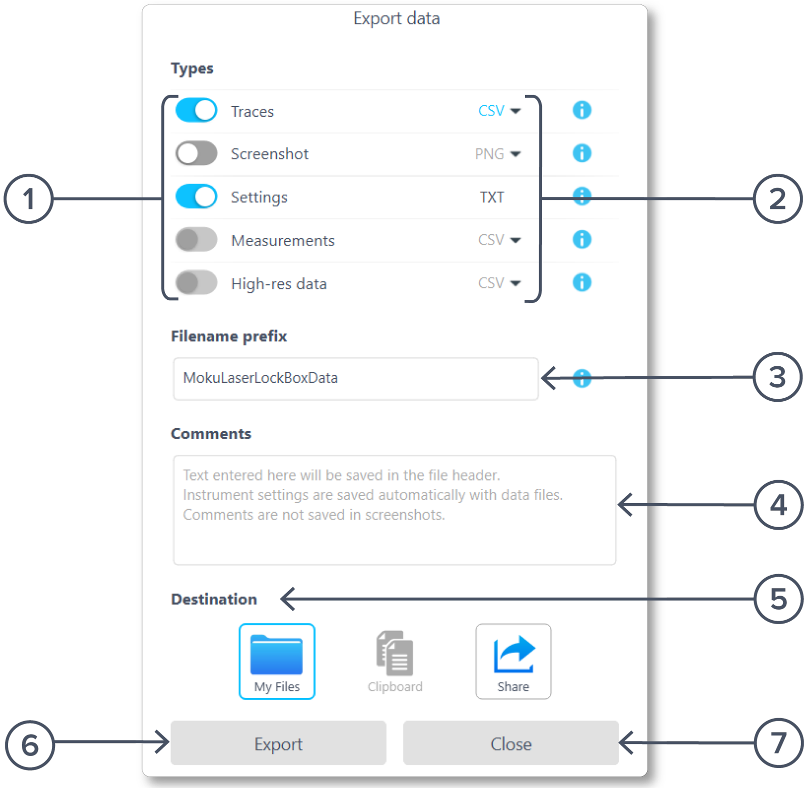


Figure 18. Data exporting User Interface and settings.

To save live data:

① Select the type of data to export:

- **Traces** Saves the trace data for all visible signal traces, in either a CSV or MATLAB format.
- **Screenshots** Save the app window as an image, in either a PNG or JPG format.
- **Settings** Saves the current instrument settings to a TXT file.
- **Measurements** Saves the active measurement values, in either a CSV or MATLAB format.
- **High-res data** Saves the full memory depth of statistic values for all visible channels, in LI, CSV, HDF5, MAT or NPY format.

② Select the **export format**.

③ Select the **Filename Prefix** for your export. This is defaulted to "MokuLaserLockBoxData" and can be changed to any filename of alphanumeric characters and underscores. A timestamp and the data format will be appended to the prefix to ensure the filename is unique.

For example: "MokuLaserLockBox_YYYYMMDD_HHMMSS_Traces.csv"

④ Enter additional **Comments** to be saved in any text-based file header.

⑤ Select the export **Destination** on your local computer. If "My files" or "Share" is selected, the exact location is selected when the Export button is clicked. Multiple export types can be exported simultaneously using My Files and Share, but only one export type can be exported to the clipboard at a time.

⑥ **Export** the data, or

⑦ **Close** the export data window, without exporting.

Logged data

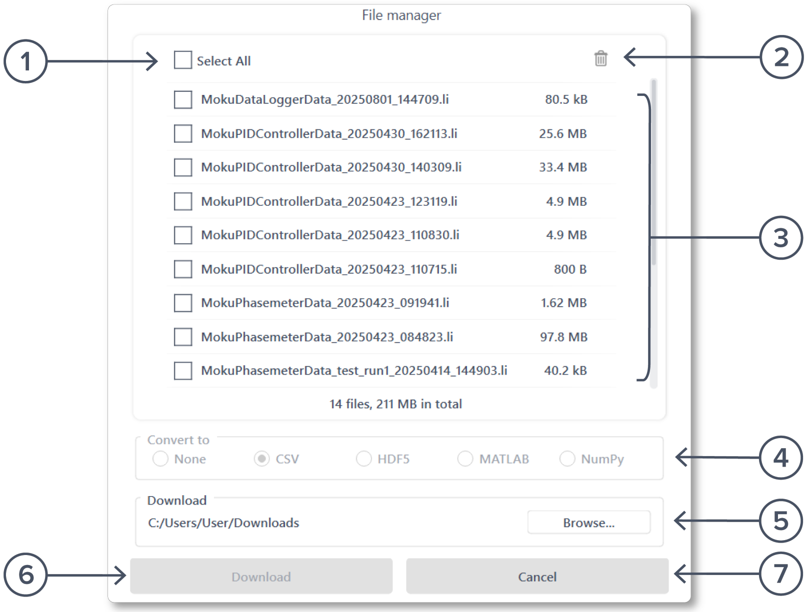


Figure 19. File exporting User Interface and settings.

To save logged data:

① **Select all** files logged to the device's memory, to download or convert.

② **Delete** the selected file/s.

③ Browse and **select file/s** to download or convert.

④ Select an optional **file conversion format**.

⑤ Select a **location** to export your selected files to.

⑥ **Export** the data.

⑦ **Close** the export data window, without exporting.

Locking settings

The Laser Lock Box is equipped with features to make laser locking easier and more intuitive for users. These features are designed specifically for assistance in finding the zero-crossing error signal and easier re-lock capabilities.

Lock Assist

The Lock Assist identifies the zero-crossing points on the error signal (probe after the setpoint). This is a visual aid for identifying the desired lock point for the control system. Thus, it is accessible only when the embedded Oscilloscope is enabled.

Click to enable the Lock Assist. This activates the Scan signal (configuration can be done here), enables the signal output, and places a Probe point after the Setpoint. The Scan signal typically operates at low frequency and thus the error signal would be closely synchronized to the Scan signal.

On the Oscilloscope, the error signal is displayed with cross-hairs to denote the zero-crossing points. Pressing on the desired lock point will adjust the output offset to the corresponding voltage and then apply the Locking stage actions as specified in the setup.

When the Lock Assist is enabled, the trigger settings are configured to synchronize the Oscilloscope traces with the Scan signal. Scrolling or zooming on the scope changes the amplitude and offset of the Scan signal. The Slow Controller can also be turned on and the offset can be varied to find the error signal for locking.

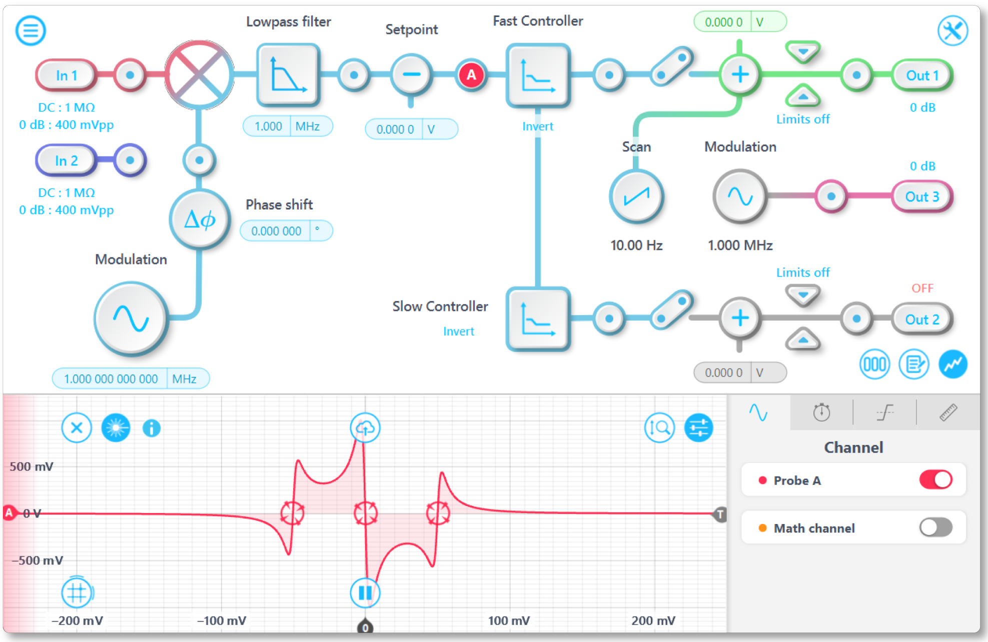


Figure 20. Using Lock Assist in the Laser Lock Box.

Scan

The Scan signal is used to apply a slow varying signal to the laser system. Typically, these are connected to the actuators of the laser to vary the frequency, phase or amplitude of the laser. With the Laser Lock Box, these can be used to find the zero-crossing point in the error signal.

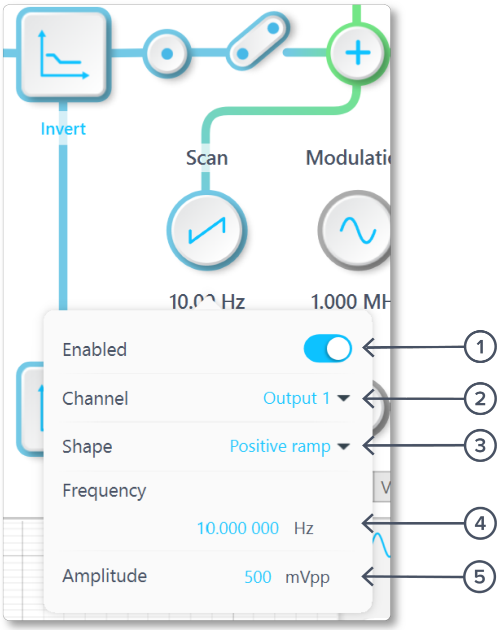


Figure 21. Scan signal settings.

① Enable/Disable the Scan signal.

② Select between output channels to output the signal.

③ Switch the shape between Positive/Negative Ramp or Triangle.

④ Type in the frequency of the Scan signal.

⑤ Type in the amplitude of the Scan signal.

The Scan signal is automatically enabled when the Lock Assist is enabled and would be used to synchronize with the error signal.

Locking stages

The Locking stages specify the behavior of the Laser Lock Box when the zero-crossing points are selected during Lock Assist. The Stages can be used to specify the order in which certain actions need to be taken. Moku Laser Lock Box supports up to three user-configurable Locking stages. The most recent stage must be disengaged before disengaging any previous stages.

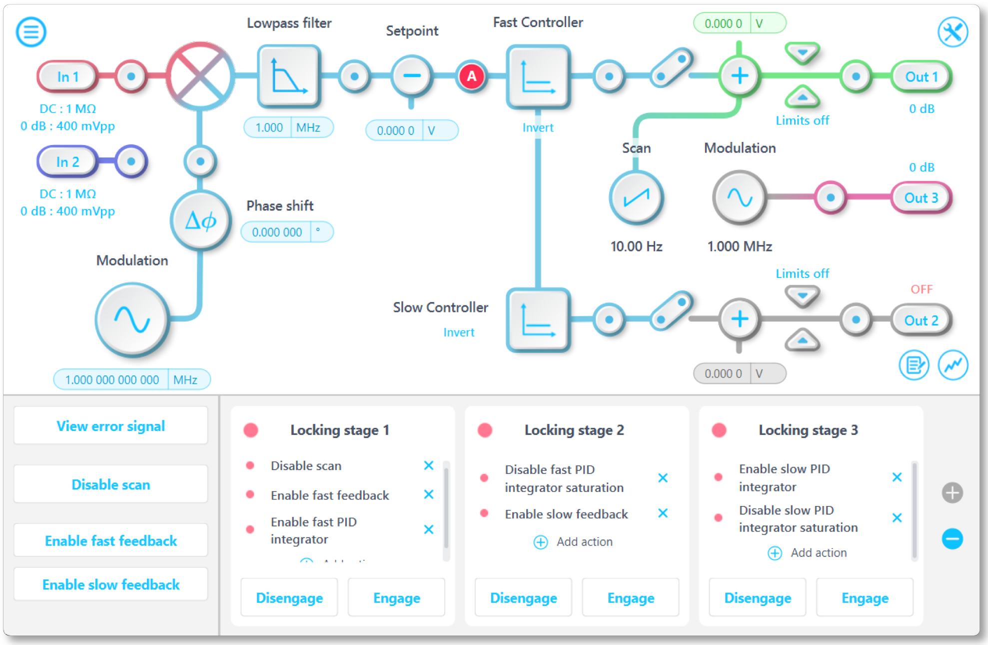


Figure 22. Locking Stages in Laser Lock Box.

The actions available on the Locking stages include:

Table 3. Actions on the Locking stages.

Parameter	Description
Disable scan	Disables the Scan signal into the output
Enable fast feedback	Closes the switch between the Fast Controller and the output.
Enable fast PID integrator	Enables the Integrator in the Fast Controller. The gain of the integrator would be the one set on the interactive plot.
Enable fast PID double integrator	Enables the Double integrator in the Fast Controller. Note that the Double integrator can only operate with the Integrator enabled.
Disable fast PID integrator saturation	Disables the saturation on the integrators in the Fast Controller.
Enable Slow feedback	Closes the switch between the Slow Controller and the output.
Enable slow PID integrator	Enables the Integrator in the Slow Controller
Disable slow PID integrator saturation	Disables the saturation on the Integrator in the Slow Controller

Examples

Tilt locking to optical cavity

Tilt locking is an alternative laser locking technique to the Pound-Drever-Hall (PDH) method, where a laser's frequency is matched to an optical cavity. Tilt locking generates an error signal by measuring the phase difference between a fundamental cavity spatial mode and a higher-order spatial mode. Compared to PDH, tilt locking does not require modulation and instead relies on a split photodiode to generate the error signal. Because it eliminates the need for phase modulators and demodulation circuits, tilt locking can offer a simpler and more cost-effective experimental setup. The typical outline of a tilt laser locking technique is as follows:

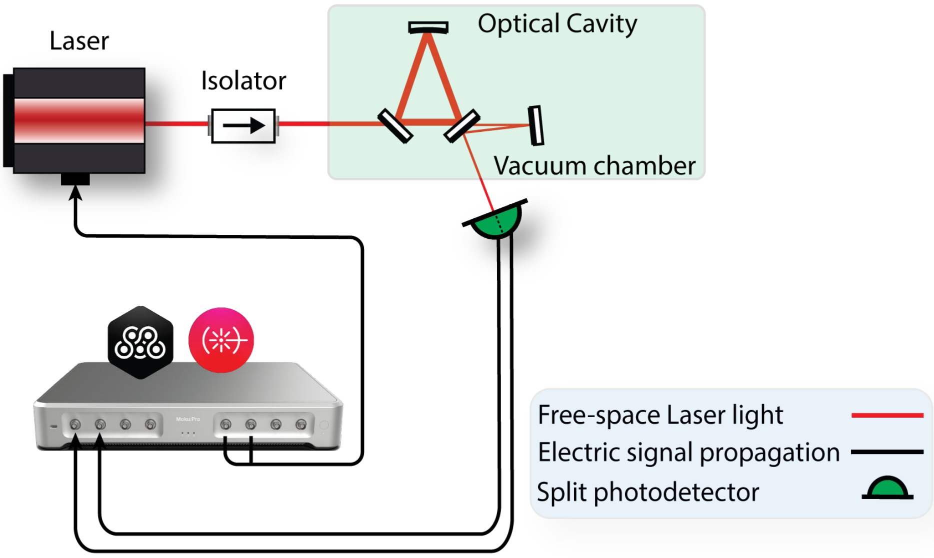


Figure 23. Experimental setup of tilt stabilization using Moku:Pro.

The laser is coupled into a cavity in the forward direction, with the transmitted field filtered to the fundamental mode and retro-reflected at a slight horizontal tilt. This tilt makes the beam couple mainly into a higher mode, allowing tilt detection using a split photodetector after the second pass through the cavity.

The Moku can then use the reflected signal to obtain the error signal by subtracting the two sides of the photodetector outputs. It is then sent to the relevant controllers, which in turn drive the laser control actuators.

Step 1: Set the Multi-Instrument Mode configuration

- In this example, Moku uses a Moku Cloud Compile slot with a Laser Lock Box to achieve lock. The Moku Cloud Compile slot performs a subtraction between the two photodiode signals before sending the differential signal for the Laser Lock Box to control the laser.
  In Multi-Instrument Mode, connect Input 1 and Input 2 to Input A and Input B of the Moku Cloud Compile. The output from the Moku Cloud Compile (Output A) is connected to the Input A of the Laser Lock Box. The output from the Laser Lock Box is connected to Output 1 and Output 2 that adjusts the laser frequency through PZT and thermal actuators.

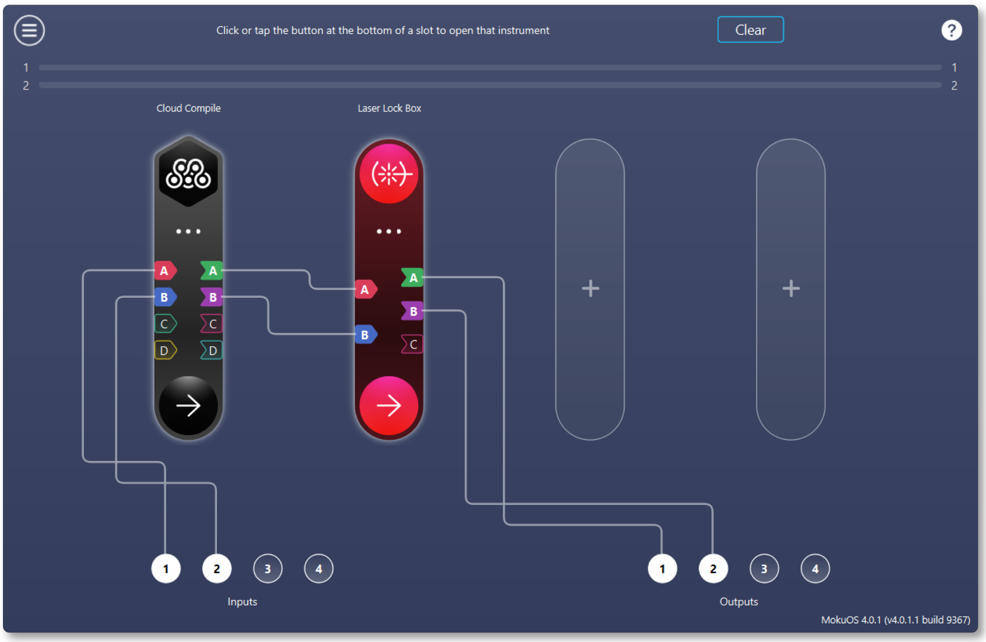


Figure 24. Multi-Instrument Mode configuration for tilt locking.

Step 2: Moku Cloud Compile: Implementing the subtractor

- Generate the bitstreams necessary for implementing the subtractor as described here using the adder example. Once the bitstream is downloaded from the compile site, upload and deploy the bitstream. *Tip: The behavior of the Moku Cloud Compile bitstream can be verified with Oscilloscope in Multi-Instrument Mode before using it for laser locking.*

Step 3 Laser Lock Box: Locking the laser to the cavity

- Select the Demodulation source to be None so that the subtracted output will pass through. Select "View the error signals" and select the to enable the Lock Assist mode. This will open the embedded Oscilloscope and put a Probe after the demodulation step. At the same time, the output will generate a Scan signal that can be used to sweep the laser frequency to find the cavity resonance. To ensure a strong error signal is achieved, optimize the following parameters:
  - By default, the Scan signal is connected to Out 1 (Piezo actuator) with a 500 mVpp triangular signal at a frequency of 10 Hz. If the cavity resonance is not within the PZT range, then enable Out 2 (Thermal actuator) and adjust the output offset until the cavity resonance can be observed. *Note that the Scan signal can also be passed to Out 2 (the thermal actuator), however a low frequency (< 10mHz) should be maintained to provide enough time to observe the cavity resonance.*
  - If the error signal is too noisy, use the Lowpass filter to filter out the noise. Reducing the cut-off frequency can improve signal visibility and make it easier to achieve the initial lock. Here we use a 1 MHz low-pass filter cut-off. *Note: Changing the Lowpass filter settings can affect the open loop response of your feedback system. After initial lock acquisition, you can revert back to a higher cut-off frequency.*

Step 4: Set the Fast Controller and enable the lock

- After obtaining a valid error signal, ensure that the Fast controller is configured with low gain and saturation for easier lock acquisition. Here, the Proportional gain is set to 0 dB and the Integrator crossover frequency is set to 1 kHz with Integrator saturation level at +20 dB.

- If the laser actuators are rated below Moku's output voltage range, ensure the voltage limits are applied as appropriate.
- In the Oscilloscope, the Lock Assist will still be enabled, with the error having cross-hairs on the zero-crossing point. This zero-crossing point can be varied by changing the setpoint to maintain the same DC level. Enable the control loop by pressing on the cross-hair. This will close the output switch and disable the Scan.

Step 5: Disabling the Integrator saturation and tuning the lock

- Enable the probe on Out 1 and observe the output signal. On the Fast Controller, disable the Integrator saturation level. If the output signal reaches the voltage limits, re-enable the saturation and lower the Integrator gain. Test the lock acquisition by enabling the Lock Assist again. A similar approach would be to start with a very low gain and gradually increase it, assuming the system allows for the desired PID response in steady state. *Note: If the open loop response shows instability with Integrator, the Integrator should be disabled*.

Step 6: Enabling the Slow Controller

- Enable Out 2 (if thermal offset is not used) and set the Slow Controller to a very low gain integrator. Close the Slow Controller switch and observe the signals in Out 1 and Out 2. The Out 1 should now center around zero, maintained by the output from the Slow Controller. If the slow output causes Out 1 to reach the voltage limits, and repeat steps 4-6, reducing or inverting the Slow controller output.

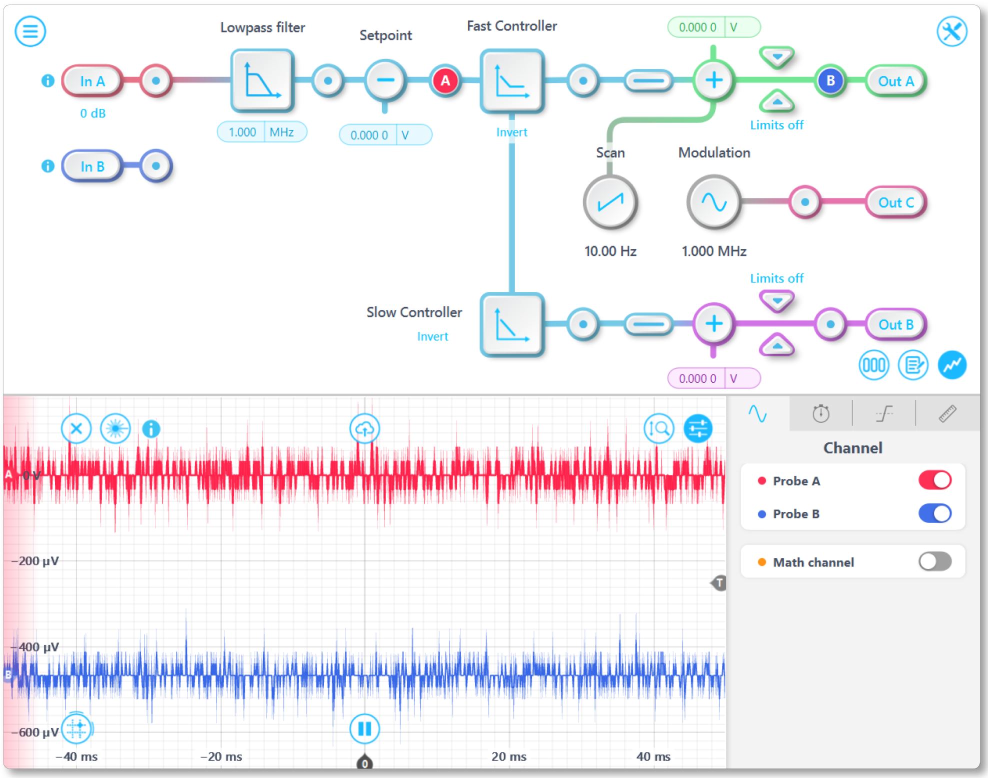


Figure 25. Observing the error and control signal after laser lock.

Locking the frequency comb to an oscillator and a laser to the frequency comb

A frequency comb is a specialized, ultrafast pulsed laser whose frequency spectrum consists of many equally spaced components. These lines can be used to estimate unknown frequencies or provide a reference to stabilize lasers. The laser is first interfered with the optical frequency comb, and then the desired beat signal between the known reference and the laser is used to stabilize the laser.

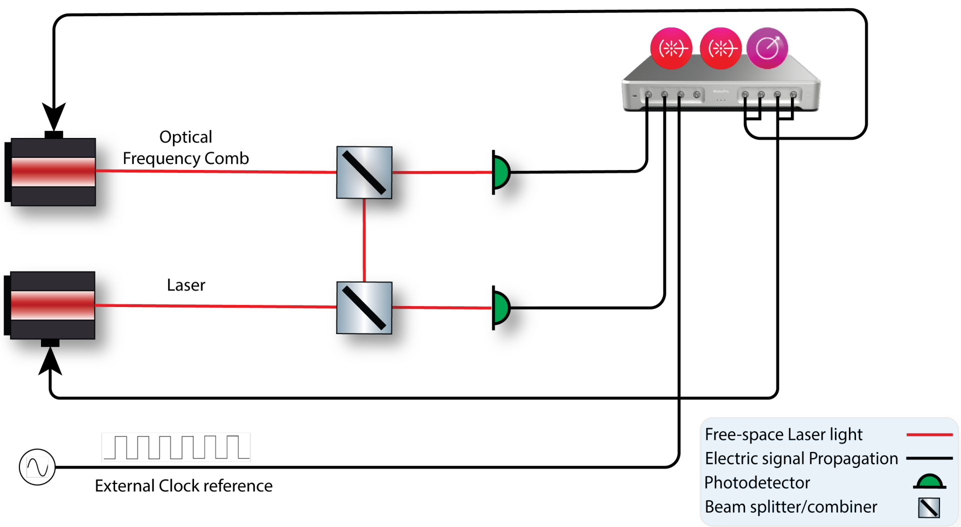


Figure 26. Experimental setup to do laser locking to optical frequency comb using Moku:Pro.

To ensure high frequency precision and stability, a common practice is to lock the repetition rate of the pulse to an external oscillator (atomic clock or GPS-disciplined oscillator). The repetition rate corresponds to the teeth spacing of the comb and is critical for subsequent lasers locked to the comb.

Consider a simple setup as shown in the diagram. The frequency comb interferes with a free-running laser to generate a beat signal detected on a photodetector. In parallel, the comb output can be detected on another photodetector as intensity pulse train. Both these photodetector outputs are connected to the Moku:Pro. An external clock signal from an atomic clock source is provided as the third input to the Moku device.

Step 1 : Set the Multi-Instrument Mode configuration

In this example, the setup would require the usage of two Laser Lock Boxes. One is used to lock the frequency comb to the external clock, while the other Laser Lock Box is used to lock a laser to the frequency comb. Input 1 is the frequency comb detector signal, while Input 2 is the beat between the frequency comb and the laser. Input 3 is the external clock signal from the atomic clock source.

In the Multi-Instrument Mode, connect Input 1 to Input A and Input 3 to Input B of the first Laser Lock Box. The output from the first Laser Lock Box, Output A, is connected to Output 1 where it actuates on the laser frequency of the comb. On the second Laser Lock Box, the Input A is from Input 2, while the outputs can be set from Output A to Output 3, and Output B to Output 4. Here Output 3 is connected to the PZT actuator while Output 4 is connected to the thermal actuator.

A Phasemeter measures the stability and performance of the frequency comb and laser, while a Spectrum Analyzer observes the beat signal between them.

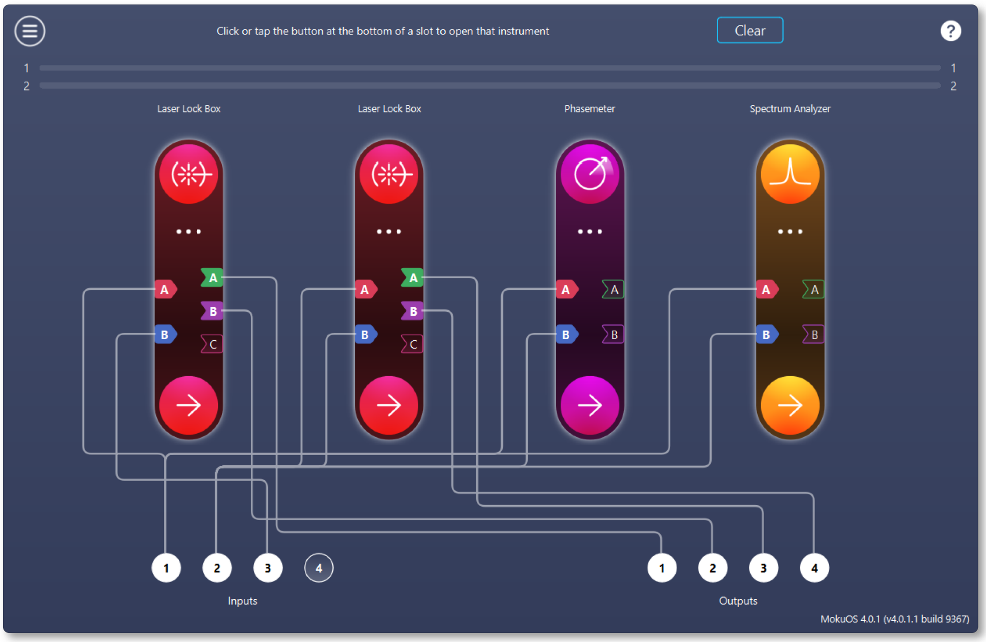


Figure 27. Multi-Instrument Mode to do laser locking and characterize performance.

Step 2 Laser Lock Box 1: Locking the comb to the external clock

Set the Demodulation source to External (PLL) and use Auto to detect the clock oscillator frequency, or disable Auto and enter the frequency manually if it is already known. With the PLL set to a 1 MHz bandwidth, re-acquire the signal to establish the oscillator's fundamental period for reference, and use the demodulated output as the phase error for locking. *When the external oscillator is at a lower frequency than the input, configure the PLL to generate a harmonic so that it aligns with the pulse repetition rate—for example, with a 10 MHz clock reference and a 25 MHz comb rate, a 2.5× multiplier ensures alignment with the pulse rate.*

Set the cut-off frequency of the Lowpass filter to 100 kHz. The larger cut-off frequency would ensure a large control bandwidth for the feedback loop.

Disable the Scan signal and enable the output. Set the Fast Controller to a low gain setting for initial lock acquisition. If Integrator is used, enable the saturation on the Integrator. Engage the Fast Controller and observe the error signals on the Probe. Alternatively, observe the results on the Phasemeter that would measure the residual phase of the setup.

Tune the Fast Controller until you get the desired/maximum bandwidth for operation. The frequency comb is now locked to the external clock.

For longer stability, set the Slow Controller to a low gain Integrator and enable the output. After engaging the feedback, observe the outputs and ensure that the two controllers are working together. If needed, toggle Invert signal to reverse the polarity of the Slow Controller output.

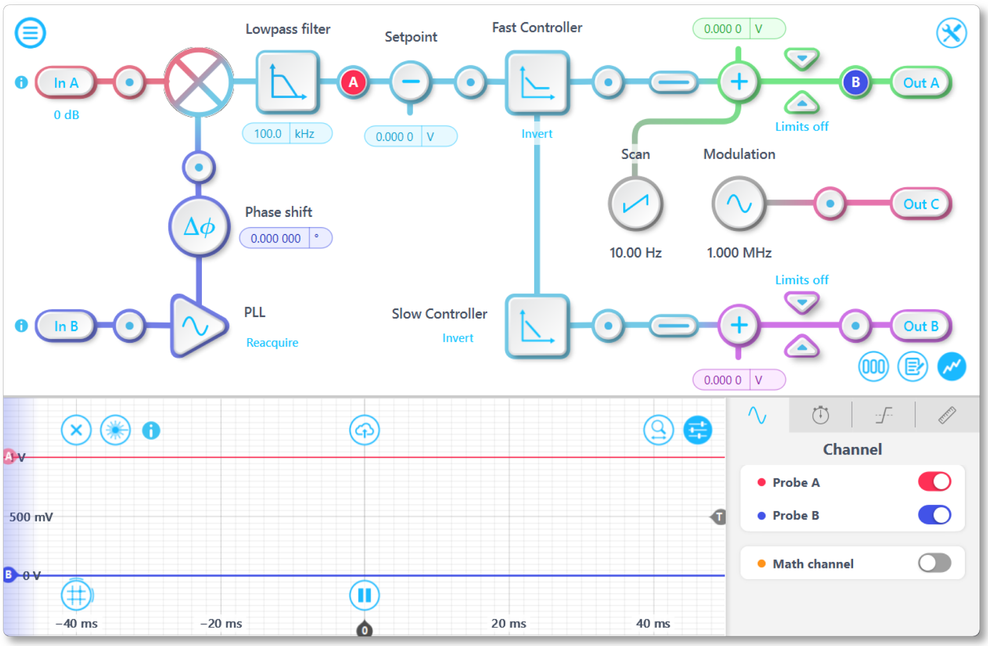


Figure 28. Laser Lock Box configuration to lock frequency comb to the external clock.

Step 3 Laser Lock Box 2: Locking the laser to the frequency comb.

Open the second Laser Lock Box and set the Demodulation source to the Internal option. After interfering the laser with the frequency comb, the spectrum of the beat signal can be observed to identify the frequency of the beat signal. The beat signal would depend on the frequency spacing of the comb and the laser frequency. The laser frequency can be given an offset through the slow output to change the corresponding beat frequency. To find the beat frequency for the local oscillator, use the Spectrum Analyzer to identify the peak frequency. Provide this measured frequency to the local oscillator to generate the phase/frequency error.

Set the cut-off frequency of the Lowpass filter to 100 kHz. The larger cut-off frequency would ensure a large control bandwidth for the feedback loop.

Disable the Scan signal and enable the output. Set the Fast Controller to a low gain setting for initial lock acquisition. If the Integrator is used, enable the saturation on the Integrator. Engage the Fast Controller and observe the error signals on the Probe. Alternatively, observe the results on the Phasemeter that would measure the residual phase of the setup.

Tune the Fast Controller until you get the desired/maximum bandwidth for operation. The laser is now locked to the frequency comb.

For longer stability, set the Slow Controller to a low gain Integrator and enable the output. After engaging the feedback, observe the outputs and ensure that the two controllers are working together. If needed, toggle Invert signal to reverse the polarity of the Slow Controller output.

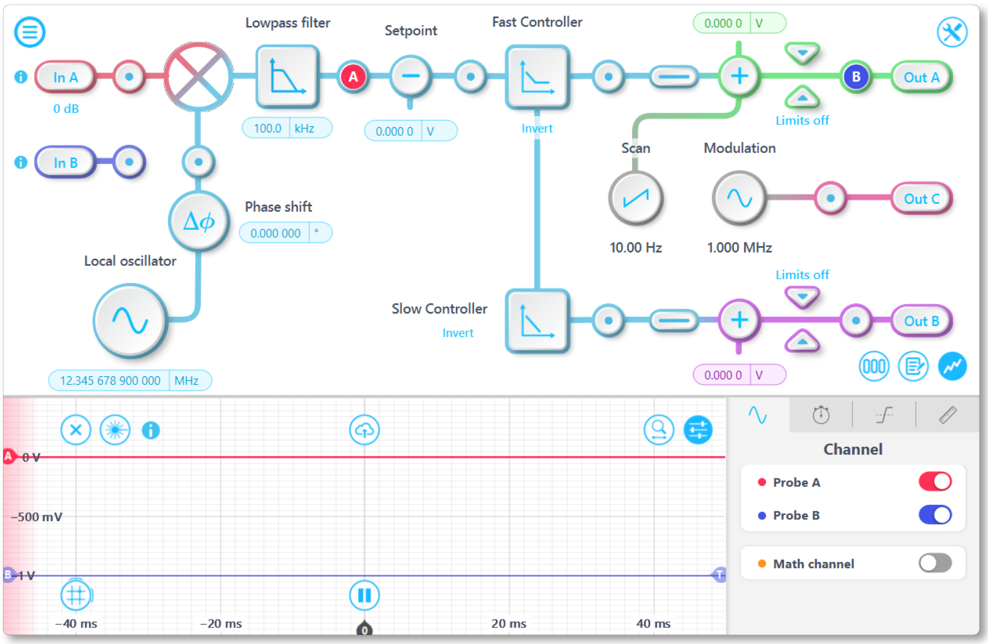


Figure 29. Laser Lock Box configuration to lock the laser to the optical frequency comb.

Step 4 Phasemeter: Logging the stability

After locking the frequency comb, measure the performance by looking at the Phasemeter. The first channel measures the repetition rate of the pulsed frequency comb. The other channel measures the in-loop performance by looking at the difference between the laser and the frequency comb. These two values characterize the performance of the locks and can measure the stability over a long period of time. Refer to Phasemeter on how to use the Phasemeter to log frequency stability.

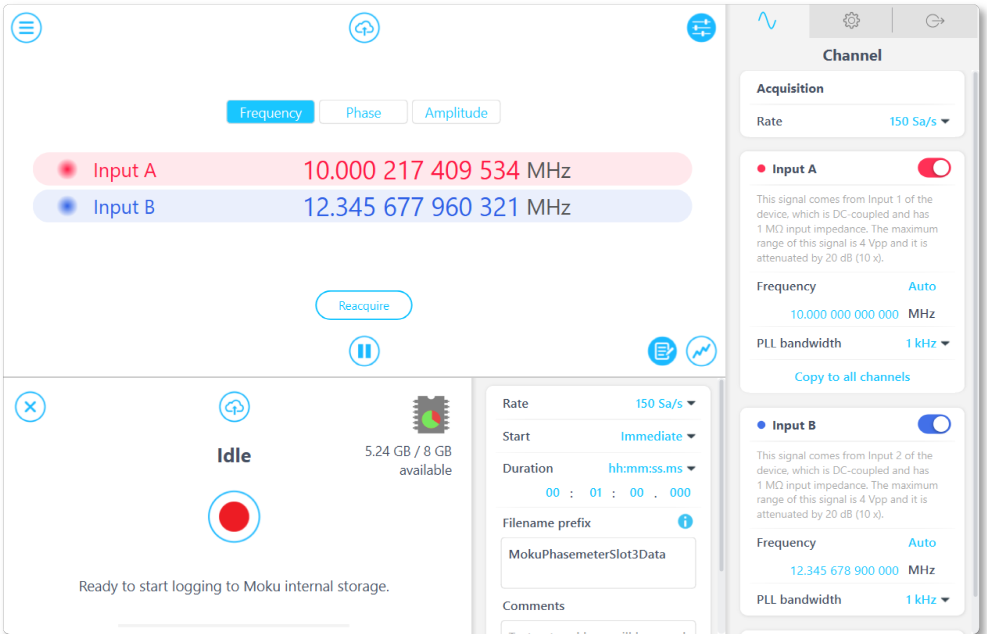
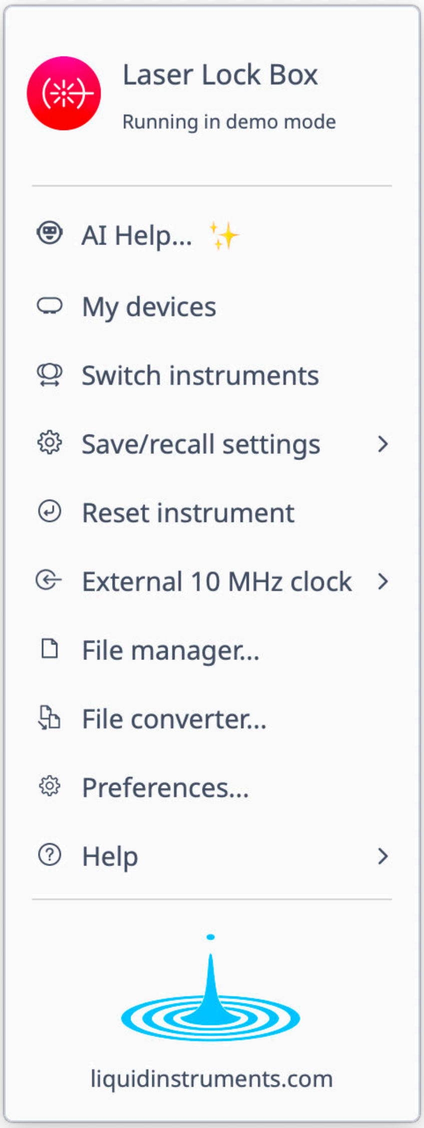


Figure 30. Phasemeter configuration to measure optical frequency comb and laser lock performance.

Additional tools

Main menu

The main menu can be accessed by clicking the ☰ icon on the top-left corner.



AI Help... Opens a window to chat to an AI trained to provide Moku-specific help (Ctrl/Cmd+F1)
My Devices returns to device selection screen
Switch instrument to another instrument
Save/recall settings

- Save current instrument state (Ctrl/Cmd+S)
- Load last saved instrument state (Ctrl/Cmd+O)
- Show the current instrument settings, with the option to export the settings

Reset instrument to its default state (Ctrl/Cmd+R)
Sync Instrument slots in Multi-Instrument Mode*
External 10 MHz clock selection determines whether the internal 10 MHz clock is used.
Clock blending configuration opens the clock blending configuration pop-up *
Power Supply access panel*
File Manager access tool
File Converter access tool
Preferences access tool
* If available using the current settings or device.
Help

- **Liquid Instruments website** opens in default browser
- **Shortcuts list** (Crtl/Cmd+H)
- **Manual** Open the user manual in your default browser (F1)
- **Report an issue** to the Liquid Instruments team
- **Privacy Policy** opens in default browser
- **Export diagnostics** exports a diagnostics file you can send to the Liquid Instruments team for support
- **About** Show app version, check for updates or licence information

File converter

The File converter can be accessed from the main menu.

The File converter converts a Moku binary (.li) format on the local computer to either .csv, .mat, .hdf5 or .npy format. The converted file is saved in the same folder as the original file.

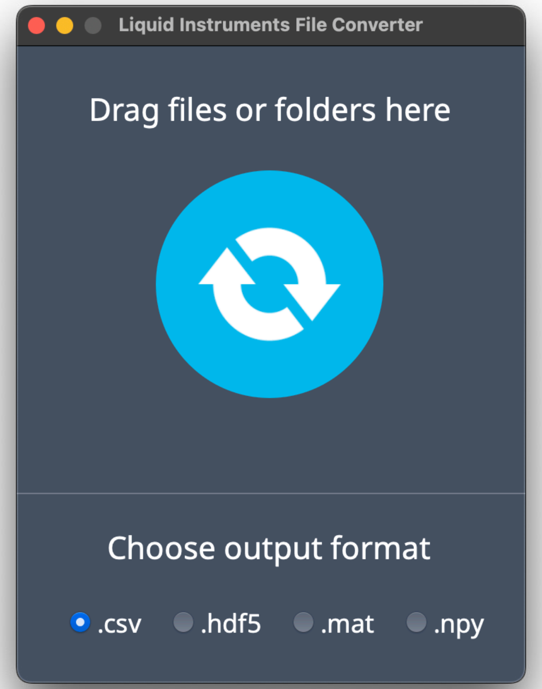


Figure 32: File Converter user interface.

To convert a file:

1. Select a file type.
2. Open a file (Ctrl/Cmd+O) or folder (Ctrl/Cmd+Shift+O) or drag and drop into the File converter to convert the file.

Preferences and settings

The preferences panel can be accessed via the Main Menu. In here, you can reassign the color representations for each channel, switch between light and dark mode, etc. Throughout the manual, the default colors are used to present instrument features.

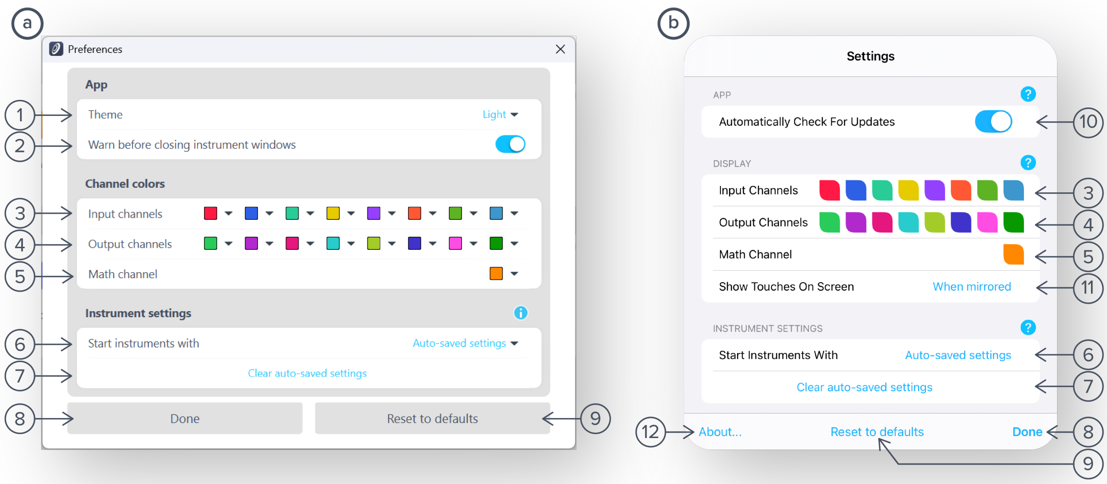


Figure 31. Preferences and settings for the Desktop (a) and for the iPad (b) App.

① Change the App theme, between dark and light mode.
② Choose if a warning opens before closing any instrument windows.
③ Tap to change the color associated with the input channels.
④ Tap to change the color associated with the output channels.
⑤ Tap to change the color associated with the math channel.
⑥ Select if instruments open with the last used settings, or default values each time.
⑦ Clear all auto-saved settings and reset them to their defaults.
⑧ Save and apply settings.
⑨ Reset all application preferences to their default state.
⑩ Notify when a new version of the app is available. Your device must be connected to the internet to check for updates.
⑪ Indicate touch points on the screen with circles. This can be useful for demonstrations.
⑫ Open information about the installed Moku application and license.

External reference clock

Your Moku may support the use of an external reference clock, which allows Moku to synchronize with multiple Moku devices, other lab equipment, lock to a more stable timing reference, or integrate with laboratory standards. The reference clock input and output are on the rear panel of the device. Each external reference option is hardware dependent, review the available external reference options for your Moku.

Reference Input: Accepts a clock signal from an external source, such as another Moku, a laboratory frequency standard, or an atomic reference (for example, a rubidium clock or a GPS-disciplined oscillator).

Reference Output: Supplies the Moku internal reference clock to other equipment that require synchronization.

If your signal is lost, or is out of frequency, your Moku will revert to using its own internal clock until the reference signal returns. If this occurs, check the source is enabled, and that the correct impedance, amplitude, tolerance, frequency, and modulation are attached to the reference. Check the required specifications in the device specsheets.

When the reference returns within range, status changes to "validating" and then "valid" once lock is re-established.

10 MHz external reference

To use the 10 MHz external reference function, ensure "always use internal" is disabled in the Moku application, found in the main menu under "External 10 MHz clock". Then, when an external signal is applied to your Moku reference input and your Moku has locked to it, a pop up will show in the app. On some devices, the external reference information will be shown in the LED status as well, more information can be found in your Moku Quick Start Guide.

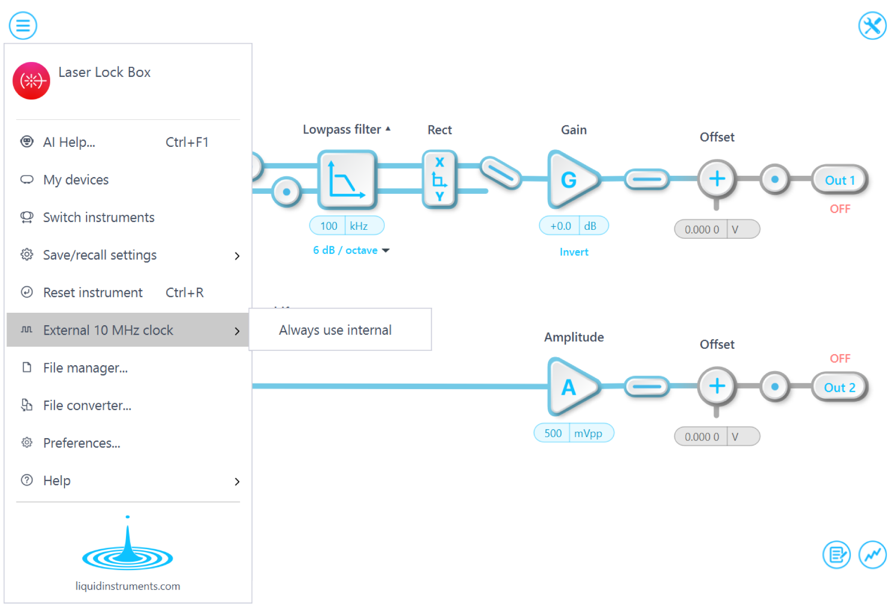


Figure 32. Moku main menu with "Always use internal" reference disabled and using an external reference.

Clock blending configuration

If available, Moku blends up to four clock sources simultaneously for more accurate phase, frequency, and interval measurements across all time scales. A low phase-noise Voltage-Controlled Crystal Oscillator (VCXO) is blended with a 1 ppb Oven-Controlled Crystal Oscillator (OCXO) for optimal wide-band phase noise and stability, which can be blended further with an external frequency reference and GPS disciplining to synchronize Moku with your lab and UTC.

The VCXO and OCXO will always be used for the clock generation signal. The external and 1 pps references are optional and can be enabled or disabled in the “Clock blending configuration...” settings from the main menu ☰. The loop bands are adjusted based on the different possible clock source configurations, shown in Figure 33, where the frequencies of the bands represent where each oscillator's phase noise dominates.

Read how the clock blending works on Moku:Delta for more details.

Figure 33. Moku clock blending configuration dialog with an external 10 MHz frequency reference and GNSS enabled.

① **VCXO jitter reference** is always used for clock generation, handling high frequency jitter with the lowest noise.

② **OCXO jitter reference** is always used for clock generation, ensuring moderate term stability.

③ **External 10/100 MHz frequency reference** uses a "10 MHz" or "100 MHz" external reference to correct drift in the local oscillator, noting your Moku will have to be restarted after each change between a 10 MHz and 100 MHz source.

④ **1 pps synchronization reference** uses an "External" or "GNSS" reference to sync with UTC and correct drift in the local oscillator. The estimated clock stability is a measure of how much the reference performance deviates relative to the local OCXO/VCXO timebase (as currently blended and, if enabled, steered by the external 10 / 100 MHz External reference).

