



SPECTROMETER

User

Manual



Narrow Range
HyperFine
Spectrometers
with a Dual Input
and a Rotatable
Grating
(HN-8995-2 and
related models)

Revised June 2023
HF-11217-2 - Rev E

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This manual is published by:

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Section 1 - About This Manual

This manual will instruct the user on the installation and operation of the spectrometer and will serve as a troubleshooting aid should any issues arise.

Document Summary

| Section | Contents |
|-----------------------------------|--|
| Section 1 - About | Overview of the information included in the spectrometer manual. |
| Section 2 - Safety | Safety and compliance considerations. |
| Section 3 - Software Installation | SpectraLoK software installation instructions. |
| Section 4 - Spectrometer software | An overview of the SpectraLoK spectrometer software. |
| Section 5 - Installation | Initial spectrometer setup procedures and alignment checks. |
| Section 6 - Calibration | Spectrometer calibration instructions. |
| Section 7 - Operation | How to obtain and optimize spectra readings using the SpectraLoK spectrometer software. |
| Section 8 - Maintenance | Spectrometer maintenance and alignment procedures. |
| Section 9 - Troubleshooting | Identifying and correcting issues with the spectrometer and the SpectraLoK software. |
| Section 10 - Appendices | Supporting documentation: principles of operation, spectral unwrapping techniques, discussion on narrowband sources, optimizing exposure, spectral artifacts, etc. |
| Section 11 - Glossary | Brief descriptions of specialized terms used in the manual. |

Section 2 - Safety and Compliance

CAUTION!

Operating the spectrometer with the housing open increases the risk of eye damage caused by scattered light emitted by the input source.

NOTICE

Optical components including the etalon and grating should be handled with care. If there is ever a need to remove or replace optical components, make sure they are carefully handled and securely mounted before operating the spectrometer.

NOTICE

To ensure reliable readings, the spectrometer must be operated within the temperature range of 18°C to 30°C (64°F to 86°F) and a humidity level of 0% to 80% (non-condensing).

CAUTION!

The top cover plate for some spectrometer models has a lip around the four edges. These are NOT handles. DO NOT lift the spectrometer by the top cover plate lips

CAUTION!

To prevent damage to the camera and other sensitive components within the spectrometer, never couple excessive optical power into the instrument. As a rough indicator, there is too much power if the light coupled into the spectrometer results in saturation of the sensor pixels at minimum camera gain and exposure. If you have concerns that your light source may damage the spectrometer, please contact LightMachinery. We can advise you on the appropriate power limits for continuous or pulsed sources with narrowband or broadband spectra.

Section 3 - Initial Setup and Software Installation

This section will guide you through the unpacking and initial setup as well as the installation of the SpectraLoK software. If a computer was included with your spectrometer, you can skip section 3.2 which refers to the software installation. If an issue is encountered during the software installation, refer to the Troubleshooting section (3.2.4) for further instructions. **Note that, depending on the model, your spectrometer might have come with additional Custom Instructions regarding certain aspects of the initial setup (calibration instructions, for instance).**

GLOSSARY

The final section of this manual contains a Glossary describing many of the specialized terms used in the manual. If you are uncertain of the meaning of any of the terms in this manual, refer to the Glossary for a definition or description.

3.1 Initial Setup

NOTICE

The spectrometer must be connected directly to a USB 3.0 port on your computer using the supplied cable. (In order to power the camera, the USB port should be capable of supplying 900 mA). Do not add a USB hub or switch.

Due to the high volume of data being streamed from the spectrometer, attempting to use a USB 2.0 port or lower may cause a connection failure. Some spectrometers have a camera that is external to the spectrometer case. For these systems, a second USB cable is supplied and must be used to connect the external camera to a second USB 3.0 port.

On units which have a USB connection for an internal LED controller or a temperature sensor, these connections can be made via USB 2.0.

Units with both an Iris camera (Teledyne Photometrics) and an external USB powered LED box or a USB powered external gas emission box (i.e. neon) may require that the light box is powered from a source other than the computer. Simultaneous current draw of the Iris camera and the light source may be too large to maintain connection.

1. Unpack your LightMachinery spectrometer and place it on a level surface.

2. Ensure that all items on the inventory list (see the **Important Information** sheet shipped with the spectrometer) are accounted for. If an item is missing, contact LightMachinery using the information at the beginning of this manual.
3. Connect one end of the included USB 3.0 cable (or cables) to the spectrometer USB port (or ports), and the other end to a USB 3.0 port on the destination computer. Depending on the model, the spectrometer USB port (or one of the ports) may be directly the camera port.
4. Connect the spectrometer's DC power cable if it came with one.
5. If your spectrometer came with a computer, SpectraLoK and the required camera drivers will come pre-installed on that device. If your spectrometer did not come with a computer, go to sections 3.2.
6. Launch the SpectraLoK software from the start menu. The main SpectraLoK window will appear.
7. You must select a camera every time you open the SpectraLoK software. Left-Click on the correct camera. The Camera, Settings, and Spectrum icons will appear, and the selected camera will be listed near the top of the screen.
8. Notice the loaded configuration file (in the File I/O section) corresponding to your spectrometer.
9. After going over Section 4 to familiarize yourself with the SpectraLoK software, complete the Initial HW Setup procedure in Section 5.

NOTICE

As the configuration file is generally modified during operation, we suggest saving a duplicate version of the original configuration file. This will allow you to revert to the original software configuration without having to download a second copy of the file.

3.2 Software Installation (ignore if your spectrometer came with a computer)

3.2.1 Computer Software Requirements

- Operating System: Windows 10 (64 bit)
- Frameworks: .NET Framework 4.5 or later.

A 32 bits version is available for older systems but may not be fully supported.

3.2.2 Computer Hardware Requirements (ignore if your spectrometer came with a computer)

Processing the images from the spectrometer sensor and converting these images into spectra requires a computer with significant processing power. Make sure your computer meets or exceeds the hardware requirements listed below:

- Peripherals: USB 3.0 port
- Memory: 8GB+ of RAM (**16GB recommended**)

- Disk Space: 100Mb+ Disk Space
- Intel processor 8th Gen Intel Core i5 (4 cores variable speed 1.6 GHz to 4.1 GHz)
- A dedicated graphic card is recommended.

3.2.3 Software Installation (ignore if your spectrometer came with a computer)

1. Make sure that .NET Framework 4.5 or higher is installed on your system:
 - a. Navigate to: Control Panel → Programs → Turn Windows Features ON or OFF.
 - b. Check the box beside .NET Framework 4.5.
2. You will find the SpectraLoK software, camera drivers, custom configuration file, and Custom Instructions document on the USB stick provided with your spectrometer. Please download all of them to your computer.
3. Install the spectrometer camera drivers. Follow the installation prompts to complete the installation.
 - a. For PixeLink cameras execute Camera_Kit.Exe
4. Install the SpectraLoK software. Follow the installation prompts to complete the installation.
5. Launch the SpectraLoK software from the start menu. The main SpectraLoK window will appear.
6. You must select a camera every time you open the SpectraLoK software. Left-Click on the correct camera. The Camera, Settings, and Spectrum icons will appear, and the selected camera will be listed near the top of the screen.
7. Load the configuration file (in the File I/O section) provided with your spectrometer.
8. After going over Section 4 to familiarize yourself with the SpectraLoK software, Complete the Initial HW Setup procedure in Section 5.

NOTICE

As the configuration file is generally modified during operation, we suggest saving a duplicate version of the original configuration file. This will allow you to revert to the original software configuration without having to download a second copy of the file.

3.2.4 Troubleshooting

This Section contains troubleshooting steps for issues that may occur during the installation or operation of your SpectraLoK software. If a solution to your problem cannot be found in this Section, please contact LightMachinery using the information at the beginning of this manual.

Before attempting the following troubleshooting steps, make sure that the computer you are using to install the SpectraLoK spectrometer software meets the minimum specifications given above.

3.2.4.1 Installer does not launch or crashes immediately

While attempting to install the SpectraLoK software, the program crashes. Please contact LightMachinery, as the SpectraLoK installer may have been corrupted.

3.2.4.2 SpectraLoK software crashes

The SpectraLoK software crashes during operation (immediately at the beginning of operation or after using it for a certain period), or the camera(s) is not shown in the list under CAMERAS (after clicking the refresh logo).

Troubleshooting steps:

1. Verify that you have the camera driver installed on your computer. If it is not installed, download the camera driver from <https://lightmachinery.com/spectrometers/support> to your computer's hard drive, launch the driver installation files and follow the installation wizard. (Do not download the driver directly from the camera manufacturer's website). If the camera driver is already installed, go to Step 2.
2. If this is the first time you are using the spectrometer and the software, or if a problem was encountered in your last attempts to use the software (e.g. repeated crashing), click **Load...** in the Main Window, and then select the original configuration file that came with your computer. It can also be found on the support website: <https://lightmachinery.com/spectrometers/support>.
3. Open the Windows task manager and check if there is a version of the SpectraLoK.exe task still running. If there is, terminate the task before launching the software again. If this does not solve the problem, go to Step 4.
4. Disconnect both the spectrometer USB cable(s) and any DC power cable from the spectrometer, wait 10 seconds, then reconnect the DC power cable first and the USB cable(s) second. Make sure you are using a USB 3.0 port(s), with a current of 900 mA. If you are using a laptop, then you may need to connect the laptop to its power supply. Launch the SpectraLoK software again. If this does not solve the problem, go to Step 5.
5. Delete the following folder (this will delete the software cached configuration):
C:\Users\[username]\AppData\Local\LightMachinery
Restart your computer, and then open the SpectraLoK software. Click the **Load...** button in the Settings window, and then select the original configuration file (initially found on the support website: <https://lightmachinery.com/spectrometers/support>). If none of the above steps resolve the issue, please contact LightMachinery for further instructions.

Section 4 – Spectrometer Software

The SpectraLoK software can be used to measure spectra in real-time, or to save measurements to CSV files for future analysis. The software also contains a “quick calibration procedure” that ensures optimal readings from your spectrometer.

The spectrometer software is compatible with most Windows devices, provided they meet the minimum device requirements (see Section 3).

Features:

- Real-time streaming spectral analysis from your spectrometer.
- Save or export data for future analysis.
- Spectrometer calibration procedures.
- Save or export raw sensor images.

4.1 How it Works

The SpectraLoK software receives the raw sensor image through the connected USB 3.0 cable. The spectrometer is calibrated using the instructions in Section 6. Once the calibration is complete, spectrum readings can be viewed in real-time or exported to CSV files for future analysis.

Several options are available for modifying the spectrum readings: background subtraction, averaging of successive images, averaging over a variable number of spectral elements, and fine tuning of the spectrum unwrapping parameters to optimize signal-to-noise ratio, contrast, and speed.

4.2 Overview of SpectraLoK Software

As is typical of many programs designed for Microsoft Windows, the different functions of the SpectraLoK software are displayed in separate views or windows. The main windows are described below:

Main Window: Opens when the software is launched and is used to open additional windows. Error messages and system notifications are displayed at the bottom of this window. The most current message or notification is also displayed at the bottom of each of the windows below.

Camera Window: Displays the image recorded by the camera sensor and features individual pixel analysis throughout the digital image.

Settings Window: Displays the parameters that can be adjusted to optimize the calibration and spectral display.

Spectrum Window: Displays the spectrum of the input light source – a graph of intensity versus wavelength, frequency, or wavenumber. It also features a variety of spectral analysis tools.

NOTICE

The Screenshots of the various SpectraLoK windows shown throughout this manual may differ slightly from those displayed on your computer screen. The SpectraLoK user interface is continuously upgraded as improvements are made, and customer feedback is incorporated. In addition, different spectrometer models have slightly different windows, depending upon the various hardware options installed.

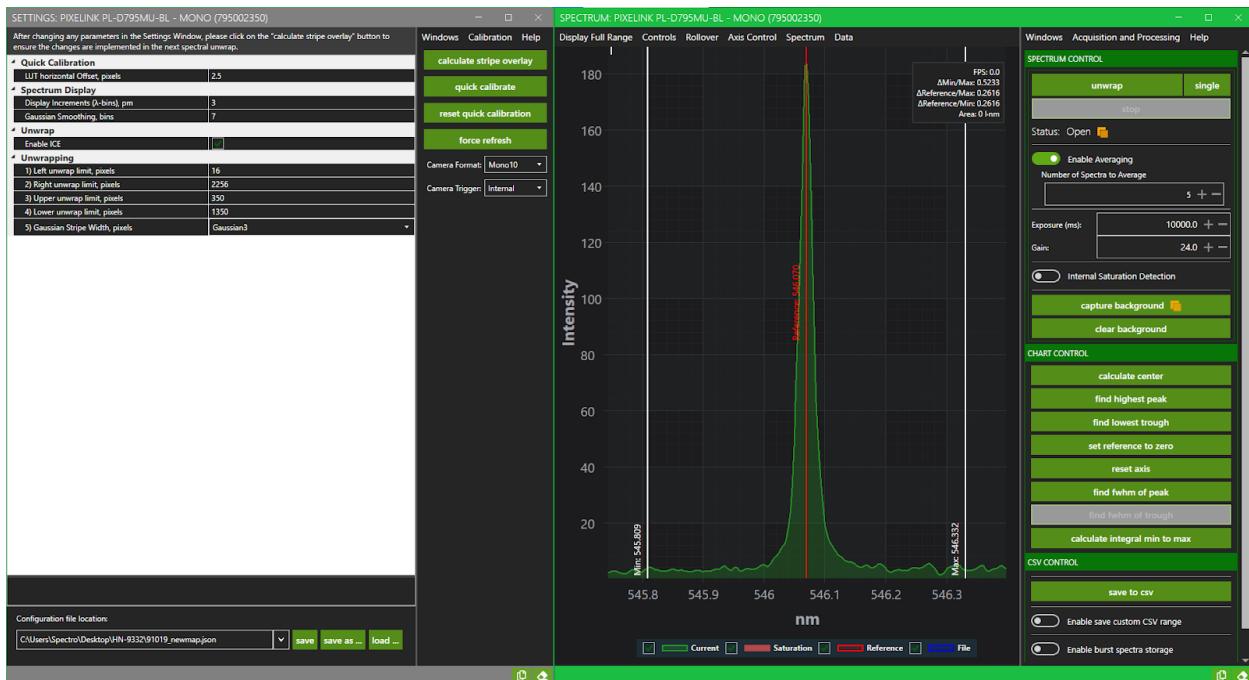


Figure 4-1 Two of the primary SpectraLoK Windows (Settings and Spectrum) displayed side-by-side

The rest of this section provides a detailed description of the SpectraLoK user interface. We highly recommend reading this section before using the software for the first time. *In particular, the tables in this section should be used as a reference whenever an explanation is required for any feature of the software.*

ATTENTION!

When the SpectraLoK software is first opened, the Main Window appears. The camera sensors detected by the system appear under the CAMERAS heading. You must select a camera sensor before proceeding. If you do not

see any cameras listed, try clicking the refresh icon beside the Cameras heading. Ensure that the sensor is set for maximum bit level (see 4.5.1 below). On opening the software, the camera bit depth will reset to the last SAVED value in the configuration file.

ATTENTION!

If you select a sensor for the first time, a window will prompt you to select a configuration file. You must select the configuration file provided on your computer's desktop, or located on the USB thumb drive included with your spectrometer if your unit did not come with a PC.

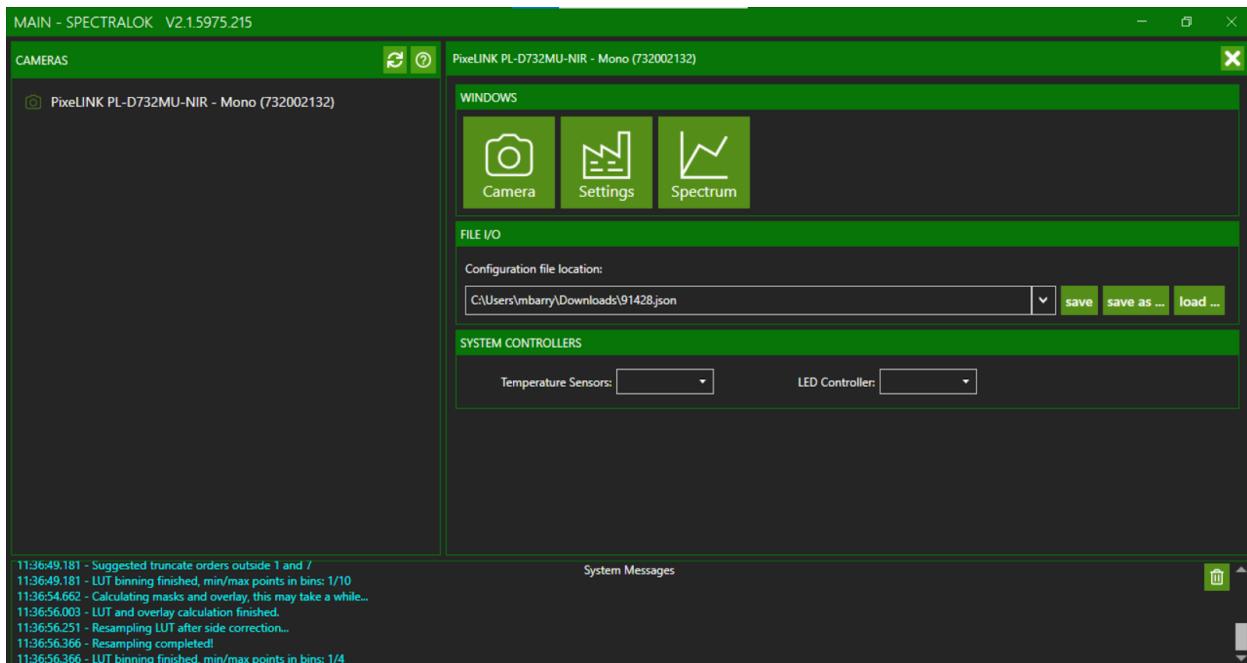


Figure 4-2 Main Window

4.3 Main Window

The various features, buttons and controls available in the Main Window are described in the Table below. (The features are described as they appear on the screen, from top to bottom). **Note that the SpectraLoK software version appears in the window header.**

| Feature | Description |
|------------------------------------|---|
| Minimize, Maximize, or Close | The conventional Windows buttons for minimizing or maximizing the Spectrum window, and closing the SpectraLoK program appear at the top right of the window. |
| CAMERAS | |

| | |
|--|--|
| | <p>All camera sensors detected by the software are listed here. You must select a camera every time you open the SpectraLoK software. Left-Click on the correct sensor. The Camera, Settings, and Spectrum icons will appear, and the selected camera will be listed near the top of the screen (see Figure 4-3). In addition to the specific camera sensors installed in each spectrometer, the list of cameras also includes a Virtual Camera. If the Virtual Camera is selected, the software offers the full range of functions described in this manual, except for the ability to capture new images or new spectra. The Virtual Camera function is designed to work only with saved images. However, it is often useful to work in the Virtual Camera mode, especially when trying to optimize many of the spectrum display parameters as described in Section 7.2.</p> <p>To unwrap a previously acquired and saved image, one must open it in virtual camera.</p> |
|--|--|

HELP

| | |
|--|---|
| | <p>Opens a drop-down menu listing all of the spectrometer manuals, titled by family. Note that the manual corresponding to your instrument is usually highlighted with a green checkmark. (If no checkmark is present, please contact LightMachinery or consult the manual on the desktop.). Click on the manual for your spectrometer to launch a new window containing the entire manual. The Table of Contents in the manual contains hyperlinks to the relevant Sections. If you need to search the manual in more detail, click on the magnifying glass or use shortcut keys Ctrl + F to bring up the search box.</p> |
|--|---|

WINDOWS

| | |
|--|------------------------------------|
| | Opens the Camera Window . |
| | Opens the Settings Window . |
| | Opens the Spectrum Window . |

FILE I/O

| | |
|-----------------------------|---|
| Configuration file location | Specifies the location for saving or loading Configuration files. Configuration files are named (***.json). |
| save | Saves changes to the Configuration file at the Configuration file location. |
| save as ... | Saves the current Configuration file under a new file name. |
| load ... | Loads a previously saved Configuration file from a chosen location. |

SYSTEM CONTROLLERS

| | |
|---------------------|---|
| Temperature Sensors | Communication port corresponding to the Temperature sensor, required for correcting any wavelength drift caused by temperature changes – populated automatically after selecting the camera. Not available on all units. |
| LED Controller | Communication port corresponding to the internal LED controller, required for calibration – populated automatically after selecting the camera. Not available on all units. Newer units have moved to an optional external LED light box. |
| System Messages | System message and error messages are displayed in this region of the screen. For clarity, these messages are time-stamped. You can delete the current message list by clicking the  icon. |

4.4 Camera Window

Click on the camera icon in the Main Window to access the Camera Window. The main portion of this window is reserved for displaying the raw image from the black and white camera sensor. Sensor pixels that are illuminated by the light source appear white or light grey; sensor pixels with little or no light falling on them appear dark grey or black. Note that the LED control buttons will also be visible with certain models.

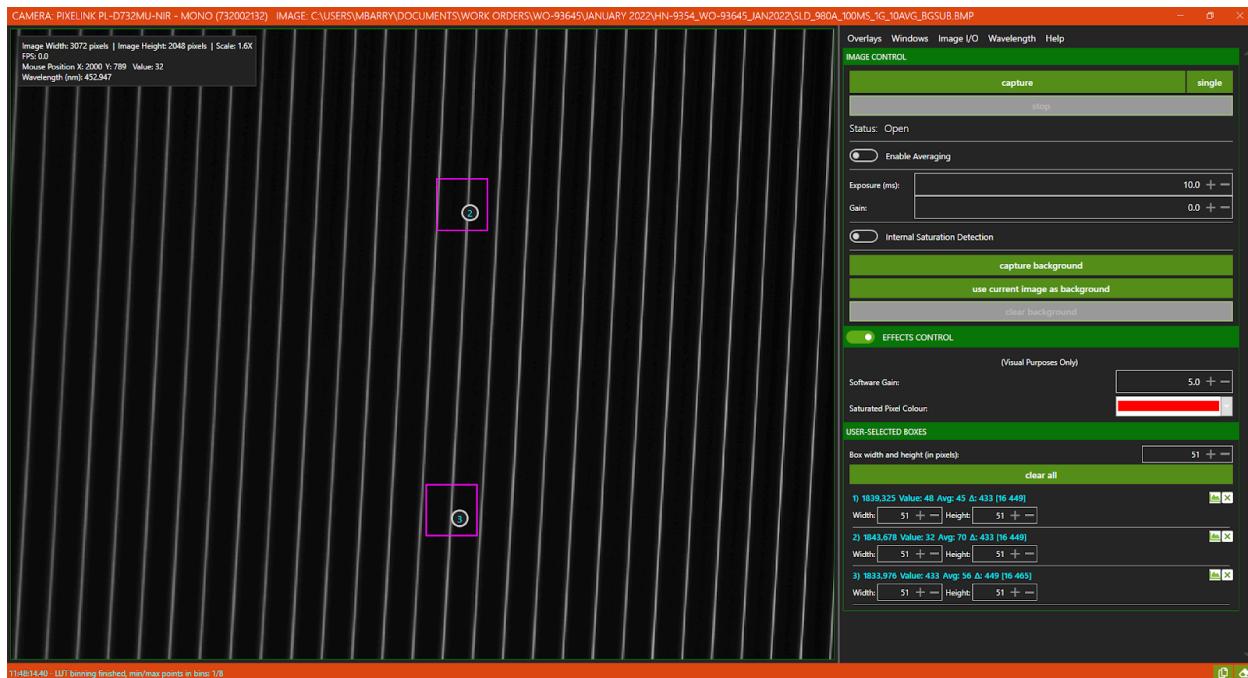


Figure 4-3 Camera Window.

Left click and drag to pan the camera view. Double-left-click to zoom out and fill the screen with the image (in the shorter dimension). Rotate the mouse wheel to zoom in and out of the image or use two-finger drag with a laptop.

The pixel coordinates (X, Y), intensity, and wavelength of your cursor position are located in the image information box in the top left corner. Note that the wavelength will display 00.000 nm until full calibration has been done (Wavelength values of 00.000 are also displayed if the cursor is positioned between stripes where there is no calibration data). For units with a fixed grating, the full calibration will have been completed at the factory.

Right click any point within the view to continuously monitor the selected pixel light intensity (Levels 0-4095 for a 12-bit sensor) of that individual pixel. The information is displayed in the bottom right corner of the Camera Window under the USER-SELECTED BOXES heading. If the user adjusts the Box width and height before right clicking, the user can also monitor the average pixel intensity within a square of numerous pixels, and the maximum intensity difference within the selected pixels.

The various features, buttons and controls available in this window are described in the Table below. (The features are described as they appear on the screen, from top to bottom).

| Feature | Description |
|---|--|
| Window Header, left side | You must select a camera every time you open the SpectraLoK software. The selected camera is identified in the window header. |
| Window Header, right side | The usual icons for maximizing, minimizing and closing the window. |
| Top left corner of sensor image. | |
| Image Width and Height | The number of pixels in the chosen camera sensor. |
| Scale | The current magnification of the sensor image |
| FPS | The refresh rate of the sensor image in Frames Per Second. |
| Temperature | The current reading of the temperature sensor inside the spectrometer (if one is installed). |
| Mouse Position | The current x and y pixel position of the cursor. |
| Value | The current sensor intensity level of the cursor pixel. |
| Wavelength (nm) | Once a calibration has been completed, the wavelength of the cursor pixel will also be updated. Shows 00.00 nm if calibration is not completed, or the cursor is positioned between stripes. |
| Overlays | |
| Overlays | Opens a drop-down menu with the options listed below. The display options can be toggled on and off by clicking on the relevant menu item or by using the keyboard short-cuts in brackets. |

| | |
|-------------------------------------|--|
| Show Grid (G) | Superimposes a grid on the sensor image. |
| Selected Pixels (P) | Indicates any pixels (and surrounding regions) that have been selected by right clicking. The default setting for this overlay is checked. |
| Stripe Overlay (S) | Displays the predicted positions of the stripes on the sensor image. These predicted stripes are used in the spectral unwrapping process. The predictions are based on the calibration of the sensor using broadband and narrowband sources, and the corrections applied in generating the Look Up Table. <i>The colour of the stripes varies from red at the left of the image to blue at the right of the image.</i> This colour change represents the change in wavelength from long on the left to shorter on the right of the camera sensor. <i>The overlay is only shown in the ROI (region of interest) area selected for unwrapping.</i> |
| Etalon Peaks (V) | Displays the predicted positions of the narrow-bandwidth blobs used in the Etalon Calibration. (Only available if an Etalon Calibration has been carried out since SpectraLoK has been opened). |
| Unwrap Area (U) | Shows the rectangular area of the sensor that is selected for unwrapping the spectrum. |
| Calibration Peak | Shows the position of the reference point for unwrapping. |
| Show Center Vertical Line (Shift+V) | Displays a vertical line at the center of the sensor. |
| <hr/> | |
| Windows | Opens a drop-down menu with the options listed below. |
| Settings | Opens the Settings Window. |
| Spectrum | Opens the Spectrum Window. |
| <hr/> | |
| Image I/O | Opens a drop-down menu with the options listed below. The display options can be toggled on and off by clicking on the relevant menu item, or using the shortcut keys in brackets. |
| Save (Ctrl + Shift + S) | Saves the current image as a bmp file. |
| Load (Ctrl + Shift + L) | Loads a saved image (The saved image must be compatible with the selected camera) |
| Import .dat float32 file ... | Imports a 32-bit float file |
| Import .dat uint16 file ... | Imports a 16-bit unsigned integer file |
| Export .dat float32 file ... | Exports raw camera data as a 32-bit float file |
| <hr/> | |
| Wavelength | Opens a drop-down menu with the option listed below |

| | |
|---------------------------------|---|
| Estimate from broadband signal | Carries out a grating calibration after a grating has been rotated to estimate the new position. See section 7.5.1 for further details. A full calibration must have been completed already at a previous grating setting. |
| Help | Opens a drop-down menu listing all of the spectrometer manuals, titled by family. Note that the manual corresponding to your instrument is usually highlighted with a green checkmark. (If no checkmark is present, please contact LightMachinery or consult the manual on the desktop.). Click on the manual for your spectrometer to launch a new window containing the entire manual. The Table of Contents in the manual contains hyperlinks to the relevant Sections. If you need to search the manual in more detail, click on the magnifying glass  or use shortcut keys Ctrl + F to bring up the search box. |
| Image Control | |
| | |
| capture | Displays a “live” feed of images from the sensor. (Greyed out when capturing). |
| single | Captures a single image from the sensor, and then stops. |
| stop | Stops the updating of images from the sensor. (Greyed out when not capturing, i.e., when the status is “open”). |
| Status | Describes the status of the camera, either open or capturing. A small icon,  , appears when Background Subtraction is enabled. |
| Enable Averaging Toggle | Enables the function described below. |
| Number of Images to Average | Determines the number of images to be averaged. Change by using the + and – buttons, or by using the keyboard to enter a new value. (You must then hit enter or click elsewhere in the window for the change to be applied). |
| Exposure (ms) | Exposure time in milliseconds. The time can be changed by clicking on + or -, or by entering a number on your keyboard (you must then click elsewhere in the window for the change to be applied). If the entered time is too large or too small, the exposure time defaults to the maximum or minimum time determined by the sensor specification. |
| Gain | Sensor gain. The gain can be changed by clicking on + or -, or by entering a number on your keyboard (you must then click elsewhere in the window for the change to be applied). If the entered gain is too large or too small, the gain will default to the maximum or minimum determined by the sensor specification. (Sensor gain is not available on all cameras). |
| Capture Background | Captures a background image that is subtracted from all future images. No light source should be present, and the values of exposure and gain should be set to the values used when imaging the light source. |
| Use Current Image as Background | Captures the currently displayed image as a background image. This is to allow users the ability to load in previously taken/saved images and utilize them for background subtraction. |

| | |
|--------------------------------------|--|
| | Note: If using Virtual Camera, load in an image, select “Use Current Image as Background”, and finally in the Camera Window select “Single” to apply the captured background to any loaded image. |
| clear background | Clears the saved background image. Once the background is cleared, no background subtraction takes place. |
| Internal Saturation Detection Toggle | Enables the function described below |
| For intensity greater than: | Any pixel with an intensity greater than the selected value, prior to applying the background subtraction, will be displayed in the colour chosen under EFFECTS CONTROL. This function is typically used to avoid saturation in the captured images. |

EFFECTS CONTROL

| | |
|-----------------------|--|
| Software Gain | This parameter can be increased to enhance the display of weak signals. It multiplies all intensity levels before displaying them but does not change the underlying image. The gain can be changed by clicking on + or -, or by entering a number on your keyboard. If the entered gain is too large or too small, the software gain will default to the pre-set maximum or minimum values. |
| Saturated Pixel Color | When EFFECTS CONTROL is toggled ON, any pixel in the display that has intensity equal to the maximum value of 4095 (in the case of a 12-bit sensor) will be displayed in red (the color can be changed by clicking on the drop-down arrow on the right). This feature is very useful in ensuring that no saturation occurs in the image, and is enabled by default when the software is launched. (However, to ensure saturated pixels are detected when background subtraction or image averaging are enabled, the “internal Saturation Detection” Toggle should also be enabled). Toggling the EFFECTS CONTROL off will disable this feature (alternatively, with the EFFECTS CONTROL on, select the colour white to effectively disable the feature). |

LED CONTROL (visible only in certain models)

| | |
|--------------|--|
| Turn On LED | Turn on the LED (if installed). Note that there is no indicator of success in the user interface. Must look to see if light is being produced. |
| Turn Off LED | Turn off the LED (if installed). |

USER-SELECTED BOXES

| | |
|----------------------------------|---|
| Box width and height (in pixels) | Defines the dimensions (in pixels) of the square that surrounds a selected pixel, and also the range of the 3-D color display obtained by clicking on the “mountains” icon. The cursor is used to select a pixel in the image. When you right-click on a pixel the following values are displayed below the clear all button: X and Y coordinate of the pixel, intensity level at the pixel, the average value of the intensity within the selected square region, and the delta symbol shows the difference between the max and min values within the square. |
|----------------------------------|---|

| | |
|----------------------------|---|
| | <p>Hold the Control key while right clicking on a pixel to draw a rectangle rather than a square. Alternatively, the X Radius and Y Radius around individual pixels can be changed once the pixel is selected.</p> <p>Click on the “mountains” icon to obtain a 3-D color display of the region around the selected pixel, or on the X to cancel the selection. Selecting a region around a pixel is used during the Etalon Calibration to identify the blobs.</p> |
| Pixel graph | Once a pixel square has been selected by right clicking on a location in the image, click the  icon to open the pixel graph window. This is a 3D plot of the pixel intensities within the rectangular in the region within the pink box. |
| Clear All | Clears all pixel selections. Clicking on the “X” icon in the appropriate row clears individual selections. |
| Banner at bottom of window | Displays the latest system message and a yellow or red symbol if there is a warning or error message. Click on the symbol, or go to the SpectraLoK Window to see all messages. Click the “delete” symbol to clear the banner messages. Click the “copy” symbol to copy the banner message onto your clipboard. |

4.5 Settings Window

Click the Settings icon in the SpectraLoK Window to access the Settings Window.

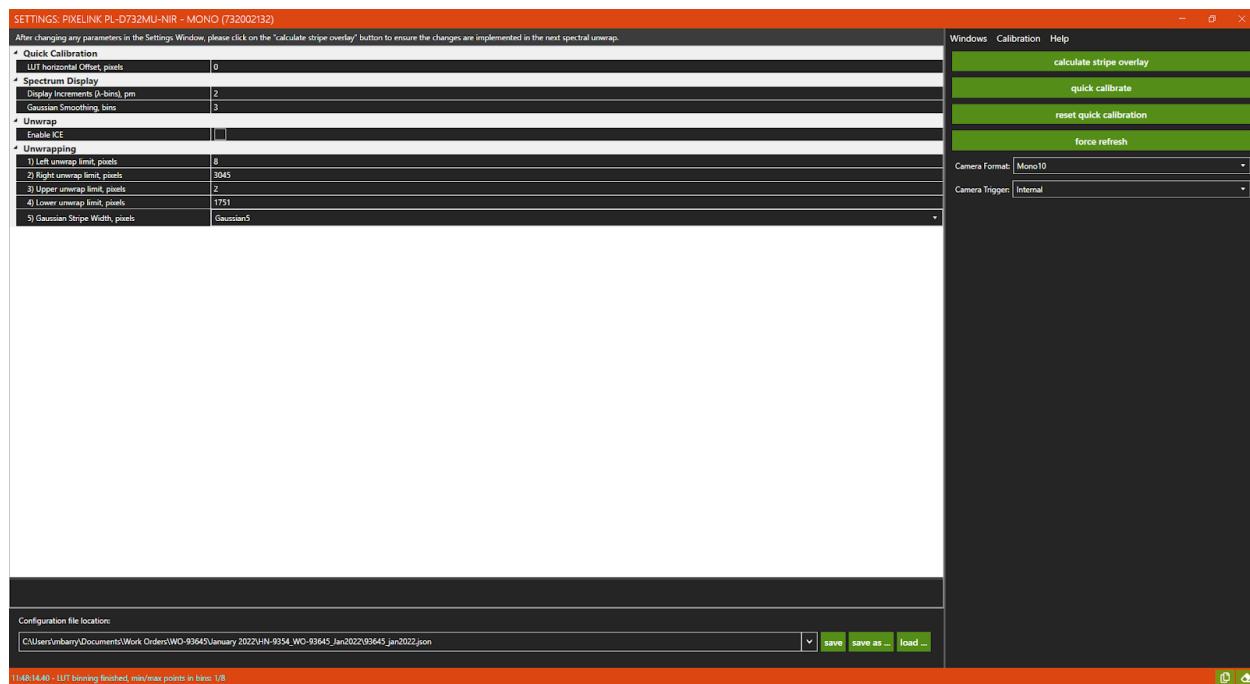


Figure 4-4 Settings Window.

The main portion of this window is reserved for displaying the parameters that are used to optimize spectrometer calibrations and spectrum unwrapping.

The various features, buttons and controls available in this window are described in the Table below. (The features are described as they appear on the screen, from top to bottom).

| | |
|---|---|
| Parameter | Description (clicking on the parameter name will provide a description at the bottom of this window). |
| Window Header, left side | You must select a camera every time you open the SpectraLoK software. The selected camera is identified in the Window header. (Different cameras have different coloured window headers). |
| Window Header, right side | The usual icons for maximizing, minimizing and closing the window. |
| Quick Calibration | |
| LUT horizontal Offset, pixels | This parameter can be used to manually shift the calculated stripe overlay to the left or right (to compensate for slight changes in the optical alignment of the instrument with time). After entering a value for the offset, hit “calculate stripe overlay” to allow the software to re-calculate the LUT. The value of this parameter is determined automatically whenever the “ quick calibrate ” button is clicked (in which case there is no need to hit “ calculate stripe overlay ”). |
| Spectrum Display | |
| Display Increments (λ -bins), pm | The (λ, I) data pairs to be displayed in the Spectrum window are sorted into “bins” with a width determined by this parameter. Hence, the parameter serves three functions. First, it determines the wavelength increment used in the Spectrum Window display. Second, it determines the wavelength separation of successive points when saving a spectrum to a CSV file. Third, the Display Increments parameter determines the width of the “bins” into which the (λ, I) pairs are sorted in the LUT. It is recommended that the minimum value of this parameter be set to 0.2 of the instrument resolution. Using a smaller value does not provide any additional information from the spectrum and may result in very large CSV files. It is sometimes useful to set the “Display increments” value to several times the instrument resolution to obtain more manageable file sizes, particularly when there are no narrow features of interest in the spectrum. |
| Gaussian Smoothing, bins | The width of the sliding window used to average the sorted (λ, I) bins in the unwrapping process. A Gaussian function is used to weight the sliding average. This parameter must be an odd number (the software will round-down an even number). |
| Unwrap | |

| | |
|----------------------------------|---|
| Enable ICE | Corrects for the variation of the intensity of stripes in the vertical direction on the sensor (from top to bottom of the ROI). Also corrects for any variations in the instrument sensitivity with wavelength. Usually enabled to reduce intensity variations caused by stitching stripes together in the spectral unwrap. To be used, in addition to selecting the checkbox in the settings window, the user must first press “calculate ICE and correct stripes” in the grating calibration window after completing a grating calibration. (The ICE coefficients are calculated automatically when using “Mapping Calibration”). |
| Unwrapping | |
| | |
| 1) Left unwrap limit, pixels | Sets the left limit on the sensor of the region to be unwrapped. Set to -1 for no limitation. The position of all limits can be seen in the Camera Window by checking the Unwrap Area overlay. |
| 2) Right unwrap limit, pixels | Sets the right limit on the sensor of the region to be unwrapped. Set to -1 for no limitation. The position of all limits can be seen in the Camera Window by checking the Unwrap Area overlay. |
| 3) Upper unwrap limit, pixels | Sets the top limit on the sensor of the region to be unwrapped. Set to -1 for no limitation. The position of all limits can be seen in the Camera Window by checking the Unwrap Area overlay. |
| 4) Lower unwrap limit, pixels | Sets the bottom limit on the sensor of the region to be unwrapped. Set to -1 for no limitation. The position of all limits can be seen in the Camera Window by checking the Unwrap Area overlay. |
| 5) Gaussian Stripe Width, pixels | This parameter determines the number of neighbouring pixels to be averaged to the left and right of the central pixel in a stripe. If this parameter is set to “None”, only the central pixel is used for the final value of the light intensity. Other choices are a 3-, 5-, or 7-pixel average. In general, this parameter should be set to approximate the width of the white-light stripes. |
| | |
| Windows dropdown menu | Opens a drop-down menu to access the Camera and Spectrum Windows. |
| | |
| Calibration dropdown menu | Opens a drop-down menu to access the following options. |
| Etalon Calibration | Opens the Etalon Calibration Window. |
| Grating Calibration | Opens the Grating Calibration Window. |
| Mapping Calibration | Opens the Mapping Calibration Window (only for use with spectrometers that ship with an External Etalon Module) |
| | |
| Help | Opens a drop-down menu listing all of the spectrometer manuals, titled by family. Note that the manual corresponding to your instrument is usually highlighted with a green checkmark. (If no checkmark is present, please contact LightMachinery or consult the manual on the desktop.). Click on the |

| | |
|--|--|
| | manual for your spectrometer to launch a new window containing the entire manual. The Table of Contents in the manual contains hyperlinks to the relevant Sections. If you need to search the manual in more detail, click on the magnifying glass  or use shortcut keys Ctrl + F to bring up the search box. |
| Buttons and dropdowns on right side | |
| | |
| Calculate stripe overlay | Forces a recalculation of the positions of the stripes displayed in the overlay, and the values stored in the Look Up Table (LUT). This recalculation often takes place automatically, but if the stripe overlay is in an unexpected position, click on this button to force a recalculation using the latest parameters, particularly after loading a new configuration file. |
| Quick calibrate | Carries out a Quick Calibration procedure to compensate for any small drifts of the predicted stripe positions. |
| Reset Quick Calibration | Removes the stripe offsets determined by previous Quick Calibration procedures, and returns the calculated stripe positions to the values determined by the most recent Grating Calibration. |
| Force Refresh | Refreshes and updates the settings after loading a new Configuration file. |
| Camera Format | Allows the user to set the bit-depth of the selected camera (see the discussion on Sensor Bit Depth in the next section). It is recommended to use the maximum bit-depth allowed by the sensor. Note that with some cameras, the bit depth is auto-selected and this dropdown will not be visible. This selector is only visible with certain cameras connected. |
| Camera Trigger | Allows the user to switch between trigger modes for the acquisition of an image by the camera. The Pixelink cameras have internal and external triggering. The Iris cameras have two types of triggering; edge mode to trigger each individual image and TriggerFirst to trigger a sequence of images. |
| | |
| Configuration file location | Specifies the location for saving or loading Configuration files. |
| save | Saves any changes to the Configuration file located at the Configuration file location. |
| save as ... | Saves the current Configuration file under a new file name. |
| load ... | Loads a previously saved Configuration File from a chosen location. |
| | |
| Banner at bottom of window | Displays the latest system message and a yellow or red symbol if there is a warning or error message. Click on the symbol, or go to the SpectraLoK Window to see all messages. Click the “delete” symbol to clear the banner messages. Click the “copy” symbol to copy the banner message onto your clipboard. |

4.5.1 Sensor Bit-Depth in Settings

A variety of camera sensors are used in the LightMachinery series of spectrometers. *For optimum performance, it is recommended that the maximum bit-depth available from the installed sensor be used.* Camera Formats are displayed as “Mono8” up to “Mono16” in the Settings Window for cameras where the user has the option to select; the former indicates an 8-bit depth where the latter indicates a 16-bit depth.

4.5.1.1 Pixelink

Spectrometers that utilize the Pixelink Cameras may have their bit depths changed in the Settings Window. The Camera Format dropdown list will display all pixel depth formats available to the camera. Figure 4-4 shows the Settings Window with SpectraLoK connected to a Pixelink camera. “Mono12” format is selected in this image, which sets a 12-bit camera depth.

4.5.1.2 IRIS or Retiga

For spectrometers that use either the IRIS or Retiga cameras, the maximum bit-depth is automatically set when the camera is connected to the computer. The IRIS camera is set to 16-bit while the Retiga camera is set to 14-bit. The Camera Format setting will not be available in the Settings Window for these cameras, as they do not support different bit depths.

4.5.1.3 Orca Fusion or Orca Fusion BT

For spectrometers that use the ORCA Fusion camera, the maximum bit-depth is automatically set when the camera is connected to the computer. The ORCA camera is set to 16-bit. The Camera Format setting will not be available in the Settings Window for these cameras, as they do not support different bit depths.

4.6 Spectrum Window

Click on the Spectrum icon in the SpectraLoK Window to access the Spectrum Window.

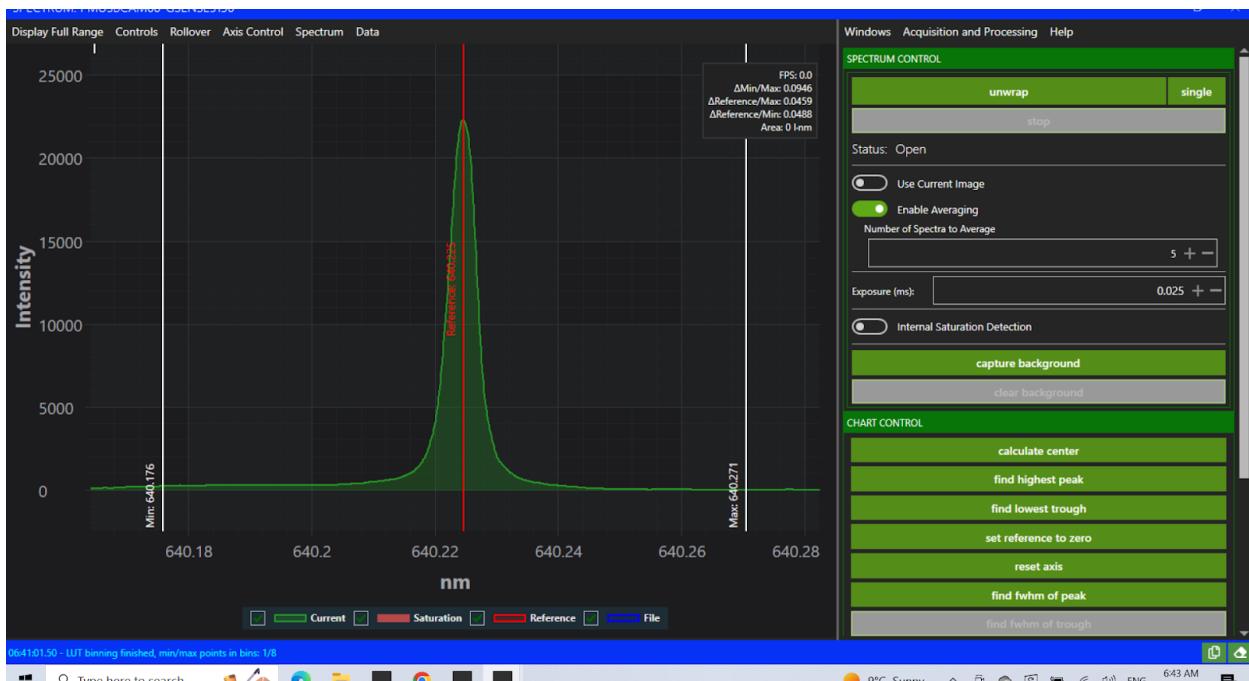


Figure 4-5 Spectrum Window.

The main portion of this window is reserved for displaying the spectrum, i.e., the graph of light intensity versus wavelength, frequency, or wavenumber.

To quickly navigate in this window (under the default settings), left-click and drag to zoom in, double-left-click to zoom out and have the spectrum fill the screen. Rotate the mouse wheel to zoom in and out. Hold down Ctrl. while rotating the mouse wheel to move the vertical (intensity) scale up and down. Hold down Shift while rotating the mouse wheel to move the horizontal (wavelength) scale left and right. If using a touchpad instead of a mouse, two-finger scroll does the same as the wheel.

Mouse over any position to obtain the wavelength and intensity corresponding to the horizontal position of the cursor (a crosshair is displayed at the cursor position and a small circle at the corresponding position in the spectrum. The wavelength is displayed along the X-axis, and the intensity is displayed on the Y).

The various features, buttons and controls available in this window are described in the Table below. (The features are described as they appear on the screen, from top to bottom).

| Feature | Description |
|---------------------------|--|
| Window Header, left side | You must select a camera every time you open the SpectraLoK software. The selected camera is identified in the Window header. |
| Window Header, right side | The usual icons for maximizing, minimizing and closing the window. |

| Dropdown Menus Along Top Left of Screen | |
|--|---|
| Display Full Range | Zooms out to display the full range. Similar to double-left-clicking. |
| | |
| Controls | Clicking displays the following dropdown menus: |
| Zoom Area | The default is checked to allow left-click and drag to zoom into a specific area of the spectrum. Uncheck to disable. |
| Mouse Wheel | Allows the function of the mouse wheel to be customized. Pan or zoom in X-direction, or Y-direction, or both. |
| | |
| Rollover | Clicking displays the following dropdown menus: |
| Show Values | Enables the display of the spectrum values at the cursor position on both X and Y axes |
| | |
| Axis Control | Clicking displays the following dropdown menus and items: |
| X Axis (Wavelength) | Allows the display of the wavelength axis to be customized (gridlines, ticks, labels, formatting). |
| Y Axis (Intensity) | Allows the display of the intensity axis to be customized (gridlines, ticks, labels, formatting). |
| Text Formatting | Within both X and Y axis dropdown sub-menus, there is the option to format text. The # means display a decimal if it exists. If you want more decimal places you need to put 0. The default is to display zero to three decimal places: 0.### Example: <ul style="list-style-type: none">• force axis to display 5 decimal places: 0.00000• display three or more decimal places (up to six): 0.000### |
| Use Log 10 Axis | If clicked, changes intensity scale from linear axis to log axis. |
| Axis Alignment | Select whether the y-axis information is on the left or right side of the plot. Found under Y-axis submenu dropdown. |
| X Range | Allows setting the min and max wavelength to be displayed on the plot. |
| Y Range | Allows setting the min and max intensity to be displayed on the plot. Also allows the user to enable auto scaling for the y-axis. |
| | |
| Spectrum | Clicking displays the following dropdown menu items |
| Measurement | Used to determine the units for the horizontal scale (change from nm to pm, or from frequency to wavenumber, for example). |

| | |
|--|---|
| Enable Waterfall Graph | Allows a “live” display of the changing spectrum in the bottom portion of the Spectrum Window |
| Hide Min / Center / Max | By default, the Min / Center / Max cursors are not displayed in the Spectrum Window. Unchecking this control and typing F causes three cursors to appear in the Spectrum Window , and also causes several extra buttons to appear under CHART CONTROL on the right side. These extra buttons allow the positions and separations of spectral features to be determined. See Chart Control below. |
| Use Baseline for FWHM | This allows the user to set a sloped baseline by setting the two white vertical bars in the area the user wants the baseline corrected. Note: this is unnecessary for FWHM of single mode lasers and emission sources with no observable fine structure since they would have a flat baseline. This is primarily intended for emissions lines over a broadband (i.e. Raman with fluorescence) or absorption features (i.e. Solar spectrum, transmission measurements). |
| Reset Min / Center / Max | Clicking on this control resets the positions of the cursors to the default positions of 1/3 rd , middle, and 2/3 rd of the full display. |
| Clear Center Cursors | Clears the central cursor (purple line) after finding the FWHM of a peak. |
| Clear reference | After a spectrum has been taken and “keep current unwrap as reference” has been clicked, a red plot appears of the reference spectrum for comparison with future unwrapped spectra. Similar to the reference check box beneath the plot, this function clears the reference. However, clicking again does not re-enable it. |
| Enable snapping of label to peak | If the feature is enabled, the label box will appear at the intensity value at the cursor X-position, allowing peaks in the spectrum to be easily identified. If the feature is not enabled, a right-click anywhere in the Spectrum Window causes a label box to appear at the cursor position. |
| Enable spectra accumulation | If checked, this feature allows successive spectra (using unwrap or single) to accumulate on top of one another. Pressing unwrap once will accumulate automatically. To accumulate single spectra, one at a time, the single button must be pressed again and again. Note that as multiple spectra are added to one another, the Y-axis may re-scale to ensure the summed intensity values stay on the screen. Uncheck the "Enable spectra accumulation" function to return to normal operation. To reset the spectrum and restart accumulation, uncheck and then recheck the "Enable spectra accumulation" function. |
| Data | Clicking displays the following three options in a dropdown menu: |
| Keep Current Unwrap | If selected, the currently displayed spectrum will be stored as the reference (red) spectrum upon next unwrap. This allows a reference spectrum to be displayed in red for comparison with future unwrapped spectra. The checkbox at the bottom of the spectral display allows the reference spectrum to be turned on and off. |
| Display Ratio <i>(useful for transmission measurements)</i> | Unwrapped intensity may be displayed as a ratio to a previously captured spectrum. To use this feature, first capture a spectrum (the denominator in the desired spectrum ratio). Then, under the Data drop-down menu click Keep Current Unwrap. Next, uncheck the Reference checkbox below the plot at the bottom of the |

| | |
|---|--|
| | spectrum window. At this point the user can take another spectrum (the numerator in the spectrum ratio), select Display Ratio from the Data drop-down. |
| Open File | Loads a previously saved spectrum csv file and displays the data in blue. This allows a recorded spectrum to be displayed for comparison with current spectra. The checkbox at the bottom of the spectral display allows the blue file spectrum to be turned on and off. Note: Spectra loaded from a csv file cannot be manipulated using the CHART CONTROLS. The CSV used is the data unwrapped and saved from the Spectrum window, not a CSV generated from the image data. |
| Checkboxes at the bottom of spectrum Window | <p>Make the current plot (green), “saturation” plot (pink), “keep current unwrap” plot (red), or “open file” plot (blue) appear or disappear.</p> |
| Information Box on Plot | |
| FPS | The refresh rate of the Spectrum graph in Frames Per Second. |
| Δ Min/Max | Displays the distance between the white lines (cursors) in nm. (Only displayed when cursors are displayed). |
| ΔReference/min | Displays the distance between the red reference line and the white min line. (Only displayed when cursors are displayed). |
| ΔReference/max | Displays the distance between the red reference line and the white max line. (Only displayed when cursors are displayed). |
| Windows | |
| Settings | Opens the Settings Window. |
| Camera | Opens the Camera Window. |
| Acquisition and Processing | Opens the Custom Acquisition and Processing Window. The features of this window are described in Section 4.7 |
| Help | |
| Help | Opens a drop-down menu listing all of the spectrometer manuals, titled by family. Note that the manual corresponding to your instrument is usually highlighted with a green checkmark. (If no checkmark is present, please contact LightMachinery or consult the manual on the desktop.). Click on the manual for your spectrometer to launch a new window containing the entire manual. The Table of Contents in the manual contains hyperlinks to the relevant Sections. If you need to search the manual in more detail, click on the magnifying glass or use shortcut keys Ctrl + F to bring up the search box. |
| Spectrum Control (at right side of window) | |

| | |
|------------------------------|---|
| unwrap | Displays a “live” feed of successive Spectrum graphs as the images are captured by the sensor. (Greyed out when continuously unwrapping). |
| single | Captures a single sensor image, displays the Spectrum, and then stops. If the “Use current Image” slider is enabled (see below), the image currently displayed in the Camera Window will be unwrapped. |
| stop | Stops updating the graphs. Greyed out when no longer unwrapping, i.e., when Status is open. (Unwrapping the image on the sensor can slow down the refresh rate of the Camera Window. Click Stop unless you require continuous spectrum updates). |
| Status | Describes the status of the camera, either open or capturing. A small icon,  , appears when Background Subtraction is enabled. |
| Use Current Image Slider | Allows the unwrapping of a captured image or a saved image that has been loaded into the Camera Window. Enable this slider whenever it is not desired to capture a new image before the unwrap |
| Enable Averaging slider | Enables the functions described below. |
| Number of Spectra to Average | Sets the number of images to be captured and averaged. |
| Exposure (ms) | Exposure time in milliseconds. The time can be changed by clicking on + or -, or by entering a number from the keyboard (for the change to be applied, you must then click elsewhere in the window). If the time entered is too large or too small, the exposure time defaults to the maximum or minimum time determined by the sensor specification. Most cameras accept millisecond input to three decimals (1 us intervals). |
| Gain | Sensor gain. The gain can be changed by clicking on + or -, or by entering a number from the keyboard (for the change to be applied, you must then click elsewhere in the window). If the entered gain is too large or too small, the gain will default to the maximum or minimum determined by the sensor specification. (Sensor gain is not available on all cameras). |
| Capture Background | Captures a background image, which is then subtracted from all future images. No light source should be present, and the values of exposure and gain should be set to the values used when imaging the light source. This can be done with averages or without. The number of images averaged is typically set to the value used when imaging the light source (or to a larger value to capture a more accurate background). |
| Clear Background | Clears the saved background image. Once the background is cleared, no background subtraction takes place. |
| Chart Control | These buttons only appear when the “Hide Min / Center / Max” button is unchecked under the Spectrum control at the top left of the Spectrum Window. Three cursors |

| | |
|-----------------------|--|
| | will appear in the Spectrum chart. The wavelength separation between each cursor is displayed at the top right of the screen. |
| calculate center | Places the Reference cursor midway between the Min and Max cursor. The positions of all cursors are displayed at the top of the screen. |
| find highest peak | Places the red Reference cursor on the point with the highest intensity within the wavelength region limited by the Min and Max cursors. Typically used when analyzing spectra from narrow band light sources |
| find lowest trough | Places the red Reference cursor on the point with the lowest intensity within the wavelength region limited by the Min and Max cursors. Typically used when analyzing spectra from broadband light sources containing absorption lines. |
| Set reference to zero | Rescales the wavelength axis by setting the position of the Reference cursor to zero. Used in conjunction with the other two cursors to measure separations between various spectral features. Used for Raman with wavenumber selected from the measurements dropdown submenu and the excitation wavelength set as the reference zero. |
| reset axis | Returns the wavelength axis to the normal default display. |
| Find FWHM of peak | Finds the Full Width Half Maximum of the peak that is between the Min and Max cursors. Note that by default, the calculation uses a flat baseline of zero. To manually choose a sloped, non-zero baseline, select “use baseline for FWHM” from the Spectrum dropdown menu. |
| Find FWHM of trough | Same as FWHM of peak, but for absorption features. Not implemented yet. |

CSV CONTROL

| | |
|------------------------------|--|
| save to csv | Saves the currently displayed spectrum to a csv file. The wavelength separation of the saved points is set by the “Display increment” and the range of saved wavelengths is determined by the “Left unwrap limit” and “Right unwrap limit” parameters in the Settings Window. The csv file is saved to the location specified by the user. |
| Enable save custom CSV range | When this slider is enabled, it allows the user to save the currently displayed spectrum or spectra acquired through the burst process via the “save to csv” button based on a custom range. This custom range is set by the values shown in the X Min and X Max boxes that appear upon activating the slider. The values shown in these boxes are directly linked to the range of the displayed spectrum and can be altered by manually writing in the values or by interacting with the chart by zooming in and out. |
| Enable burst spectra storage | When this slider is enabled, the user can save a series (or burst) of spectra as csv files to a specified location (either a folder on the computer or external storage). The number of spectra to be stored is determined by the value set under the Enable Burst slider (the default value is one) |

| | |
|-------------------------------|---|
| Number of Images to Burst | When the Enable Burst slider is activated, this parameter allows the number of successive spectra in a burst to be defined. The default value is one. If it is desired to quickly capture many images/spectra, the “Enable post capture unwrap” slider should be activated (see below). (Each spectrum may be the result of averaging several images, as determined by the value of the “Number of Spectra to Average” parameter). |
| Enable post capture unwrap | If enabled, this option allows SpectraLoK to capture and store a series of images for processing after all of the images are captured. The spectra from the processed images will be saved to a user specified location as a series of csv files. This option allows the software to capture images at much higher speeds, limited only by the exposure time or maximum camera frame rates, rather than the unwrapping speed. Note that this option uses a large amount of memory which may cause instability in SpectraLoK if the number of images/spectra is set to ~100 or more. |
| Enable hard drive buffering | This option may be enabled if the user requires a large number of images to be processed using the “post capture unwrap” functionality (see above). The images will be temporarily stored in the computer’s hard drive (rather than in RAM) and then saved as a series of csv files in the user specified location after the processing is completed. Note that this option will allow for a much larger number of images to be captured in a burst, but the processing time will be increased. |
| Enable timed spectra storage | When the slider is enabled, the inputs Time Between Spectra and Length of Time to Capture (seconds) become visible. The first sets how often to capture a frame and for how long to run. Each capture is saved to Location (see entry below). |
| Time between spectra (s) | Sets how often to capture a frame (in conjunction with exposure) by putting a pause between successive spectra. |
| Length of time to capture (s) | How long to run timed spectra storage. In conjunction with time between spectra and exposure, results in the number of spectra taken. |
| Location | Determines the file location where the csv spectra and burst spectra are saved. Saving burst spectra will result in the filename being appended with the spectra number starting at 1. For example, Spectra_1, Spectra_2, ..., Spectra_7. Note that once location has been selected, clicking save on the pop-up window does not save the file, only the location to be saved. The save to csv button still needs to be clicked for individual spectra for non-timed spectra storage. |
| Banner at bottom of window | Displays the latest system message and a yellow or red symbol if there is a warning or error message. Click on the symbol, or go to the SpectraLoK Window to see all messages. Click the “delete” symbol to clear the banner messages. |

4.7 Acquisition and Processing Window

Click the “Acquisition and Processing” button in the Spectrum Window to access the Custom Acquisition and Processing Window.

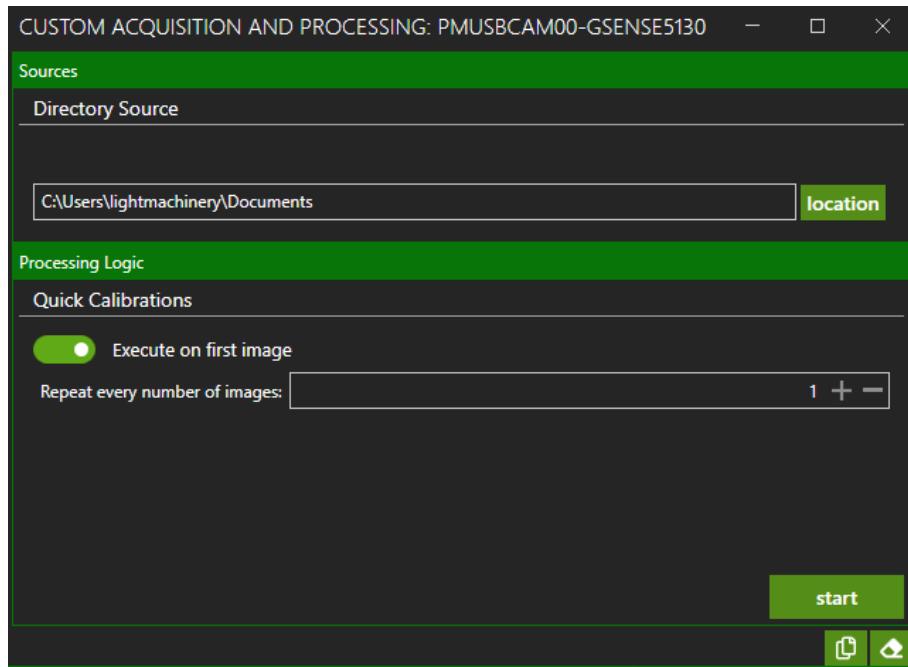


Figure 4-6 Custom Acquisition and Processing Window.

The various features, buttons and controls available in this window are described in the Table below. (The features described are grouped in sections as they appear on the screen, from top to bottom).

| | |
|---------------------------|--|
| Parameter | Description (clicking on the parameter name will provide a description at the bottom of this window). |
| Window Header, left side | You must select a camera every time you open the SpectraLoK software. The selected camera is identified in the Window header. |
| Window Header, right side | The usual icons for maximizing, minimizing and closing the window. |
| Sources | |
| location | Determines the file location of the saved images to be processed. |
| Processing Logic | |
| Execute on first image | Toggling ON will execute a quick calibration on the first image upon clicking the “start” button (setting to ON is recommended). The images are processed in alpha-numerical order (e.g. NAME_001, NAME_002, etc). |

| | |
|-------------------------------|--|
| | |
| Repeat every number of images | Determines the number of images between each quick calibration upon clicking the “start” button. Together with the “Execute on first image” field, it determines on which images of the selected location a quick calibration will be performed. |
| start | Unwraps each image in the selected location and saves the corresponding spectrum as a csv file in the same location. The “Execute on first image” toggle and the “Repeat every number of images” field determine on which images a quick calibration will be executed. The LUT horizontal offset parameter used to unwrap each image is determined by the quick calibration logic (for more details, see section 4.7.1 Post Acquisition Automated Unwrap). |

4.7.1 Custom acquisition and processing function

The custom acquisition and processing function is a tool to process a large number of camera images once they have been acquired. This section contains step-by-step instructions to perform a series of quick calibrations and unwraps of sequentially acquired bmp images, based on their file names (alph-numerical order, e.g. NAME_001, NAME_002, etc). The function allows the user to unwrap a large number of images from a specific directory and save the resulting spectra as csv files. The user can choose at which frequency quick calibrations are executed (repeat every X number of images) prior to unwrapping their respective spectrum. For example, a quick calibration can be performed every 5 images. The LUT horizontal offset parameter used to unwrap a given image in the sequence corresponds to the one determined by the latest quick calibration.

As an example, the Automated Unwrap function is particularly useful for quickly unwrapping a group of images acquired during a mapping experiment, while taking into account any small drifts in the horizontal stripe positions that may be caused by temperature changes, etc.

Procedure to unwrap a series of images:

1. Use the “Acquisition and Processing” button of the Spectrum Window to access the Custom Acquisition and Processing Window. Note that all other SpectraLoK windows are disabled when the “Acquisition and Processing” window is open. To re-enable them, close the “Acquisition and Processing” window.
2. Under “Directory Source”, in the Source section, use the “location” button to select the directory of the group of bmp images.
3. Under “Quick Calibrations”, in the Processing Logic section, toggle ON or OFF “Execute on first image” as needed.

4. Using the “Repeat every number of images” field, enter the appropriate numerical value to achieve the desired quick calibration logic. See table below for examples.
5. Press “start” to launch the quick calibration and unwrap process. The unwrapped spectra will be saved as csv files in the previously selected directory source. This process can take a few minutes to complete.

Examples of quick calibration processing logic:

| “Execute on first image” toggle | “Repeat every number of images” field | Resulting quick calibration processing logic |
|---------------------------------|---------------------------------------|--|
| ON | 0 | Quick calibration is only executed on the first image. The resulting LUT horizontal offset parameter is applied on the first image and on every subsequent image (if applicable) to unwrap their respective spectrum. |
| ON | 1 | Quick calibration is executed on all images. The LUT horizontal offset parameter from each quick calibration is applied to the corresponding image to unwrap the spectrum. |
| ON | 2 | Quick calibration is executed on the first, third, fifth, ... images of the selected location. The LUT horizontal offset parameter of the first image will be applied to the first and second images to unwrap their spectrum. The LUT horizontal offset parameter of the third image will be applied to the third and fourth images to unwrap their spectra, etc. |
| OFF | 0 | There is no quick calibration run executed. The LUT horizontal offset parameter of the selected configuration file is used to unwrap all the spectra. |
| OFF | 1 | The LUT horizontal offset parameter of the selected configuration file is used to unwrap the spectrum of the first image. A quick calibration is executed on every subsequent image. Each resulting LUT horizontal offset parameter is applied to its corresponding image to unwrap the spectrum. |
| OFF | 2 | The LUT horizontal offset parameter of the selected configuration file is used to unwrap the spectrum of the first and second images. A quick calibration is executed on the third, fifth ... images. The LUT horizontal offset parameter of the third image will be applied to the third and fourth images to unwrap their spectrum. The LUT horizontal offset parameter of the fifth image will be applied to the fifth and sixth images to unwrap their spectra, etc. |

4.8 Grating Rotation Stage Window

ATTENTION!

This section only applies if your spectrometer has a motorized grating stage installed.

In the Main window, select the Rotation Stage using the dropdown menu and then click on the Rotation icon in the Main window to access the Grating Rotation Stage window.

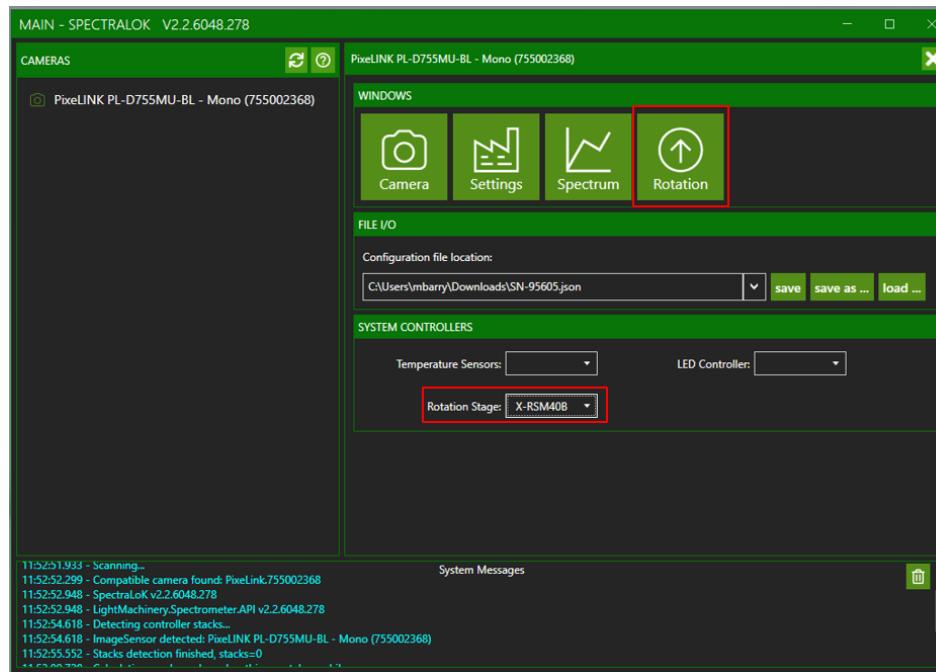


Figure 4-7 Outlining the Rotation Stage menu and Rotation window icon in the Main window.

In the Grating Rotation Stage window there are two sets of Position controls and a dropdown menu that can be accessed by clicking the “Grating Rotation Stage” header. The stage can be rotated via the Position controls by either entering the desired angle of the rotation stage in degrees or the desired wavelength in nanometers under their respective labels followed by clicking on the go! button. Progress is reported at the bottom of the window.



Figure 4-8 Grating Rotation Stage window.

The various features, buttons and controls available in this window are described in the Table below.

Grating Rotation Stage dropdown menu

| | |
|--|--|
| Save current position | Saves (i.e., stores) the current position of the axis. |
| Go to saved position | Rotates the axis to Home and then to its saved position. |
| Home | Homes the axis. Upon homing, the axis moves towards one end of its travel range until it reaches a fixed reference point. Homing takes place when this Home button is pressed, but also occurs automatically prior to moving to a position via the “go!” buttons and prior to moving to its saved position upon clicking “Go to saved position”. |
| Common buttons in Position controls | |
| go! | Moves the axis to the position specified in the field immediately on its left. Before moving to the requested position, the stage will first move to the home position. Moving to the home position minimizes any backlash errors in the encoder. |

Section 5 - Hardware Installation

This Section will guide you through the initial setup and alignment check of the LightMachinery spectrometer. Once you have completed the installation, Section 6 (Calibration) will provide information on the “Quick Calibration” function. Section 7 (Operation) will then walk you through the steps for measuring spectra.

GLOSSARY

The final section of this manual contains a Glossary that gives a brief description of many of the specialized terms used in the manual. If you are uncertain of the meaning of any of the terms in this manual, refer to the Glossary for a definition or description.

5.1 What's in the Box?

The Important Information sheet that is shipped with your spectrometer provides an inventory list of all of the items shipped with your spectrometer. Your unit may come with Custom Instructions with a schematic specific to your model.

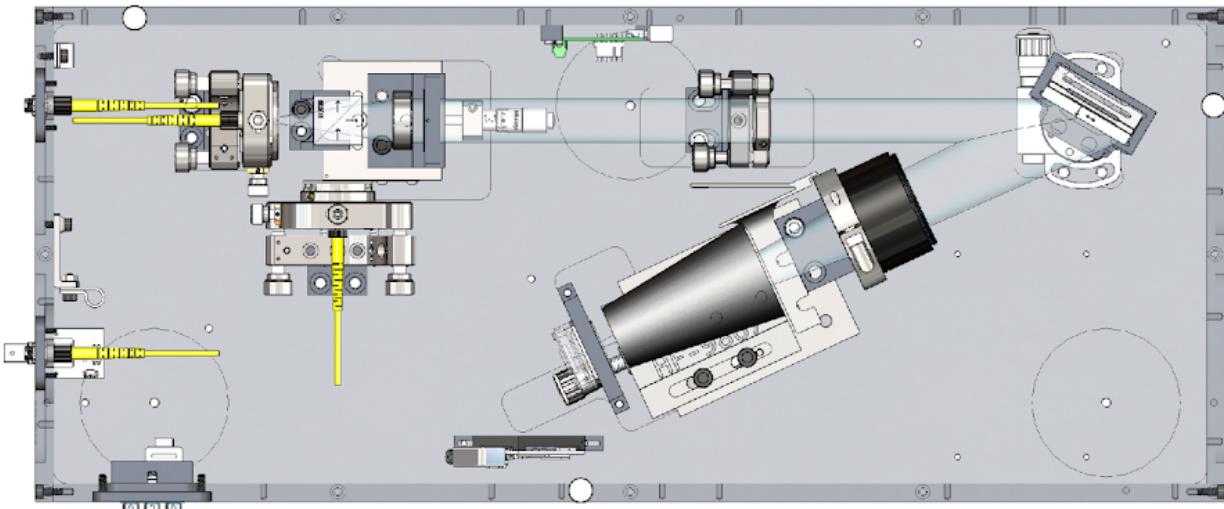


Figure 5-1 Typical layout of a dual-input narrow range Hyperfine spectrometer with rotatable grating.

5.2 Initial Setup

Ensure you have completed the initial setup described in Section 3.1 (and 3.2 if applicable) before operating your spectrometer for the first time or if the spectrometer is subsequently subjected to significant mechanical disturbance. **Note that, depending on the model, your spectrometer might have come with additional Custom Instructions regarding certain aspects of the initial setup (regarding unpacking, for instance).**

NOTICE

The spectrometer camera must be connected to a USB 3.0 port on your computer. (In order to power the camera, the USB port should be capable of supplying 900 mA). Due to the high volume of data streamed from the spectrometer, attempting to use a USB 2.0 port or lower may cause a connection failure.

ATTENTION – Connecting a light source

Light sources are usually connected to the Spectrometer by fiber optic cable. Only fiber optic cables with FC/UPC or FC/PC connectors are compatible with the input fiber optic port (unless specified otherwise...i.e. model HF-9332); fiber optic cables with SMA or FC/APC connectors require a hybrid patch cable. Remove the Fiber Optic Port protective cover. Properly align the FC/UPC or FC/PC fiber optic cable and fasten the connector. Your Custom

Instructions may provide additional guidance on how to connect light sources to your spectrometer.

NOTICE

The fiber optic cable connected to the spectrometer during calibration should remain connected for all subsequent measurements, when possible. Installing a table clamp helps to stabilize the fiber optic cable before it enters the spectrometer.

To complete the initial setup:

1. Ensure all items on the inventory list are accounted for. If an item is missing, contact LightMachinery using the information at the beginning of this manual.
2. Place the spectrometer on a level surface.

Ensure that one end of the included USB 3.0 cable is connected to the spectrometer USB port and the other end to a USB 3.0 port on the computer running the spectrometer software.

Ensure that the DC power supply is connected to the spectrometer, if your unit has such an input. Figure 5-2 shows a typical I/O Interface for HyperFine spectrometers (note that not all models are equipped with LEDs or DC power, and some models have additional USB ports).



Figure 5-2 Typical I/O Interface for HyperFine spectrometers (note that not all models are equipped with LEDs or DC power, and some models have additional USB ports).

5.3 Alignment Checks and Optimization

After the spectrometer has been unpacked and the software installed, a quick check of the optical alignment is needed, and possibly an alignment adjustment. In addition to the procedures provided below, additional information can be found in Sections 7 (Operation) and 8 (Maintenance). Performing the alignment check described below at regular intervals is recommended to ensure the light source is optimally coupled into the spectrometer.

ATTENTION

Please do not hesitate to contact LightMachinery if you would like additional information on how to set up your unit and ensure that its alignment is optimal.

Refer to the instructions below. It is required – but not necessarily sufficient – to confirm that i) a broadband source produces on the camera a signal consisting of distinct stripes similar to those shown in Figure 5-3 and ii) a narrow-band source produces on the camera a signal consisting of distinct blobs similar to the one shown in Figure 5-4 (or as an alternative to ii) a source with multiple narrow-band features produces on the camera a signal consisting of series of distinct blobs, an example of which is shown in Figure 10-10 in Appendix C).

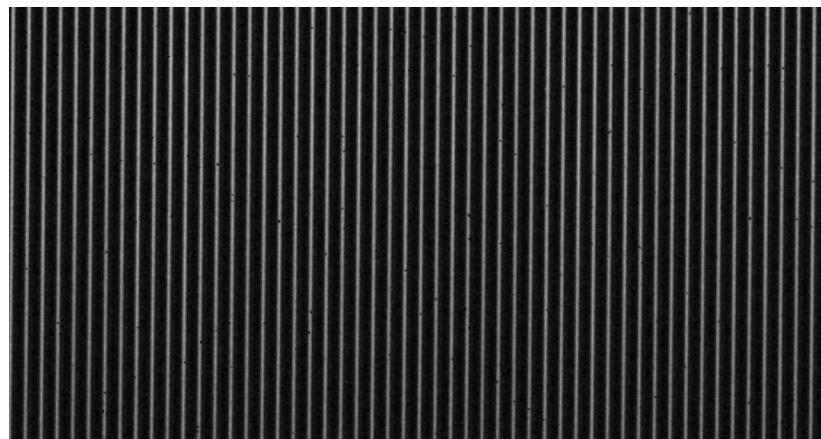


Figure 5-3 Example of broadband stripes as seen in the Camera Window. Note that the separation, width, and sharpness will vary between spectrometer models and wavelength ranges within the same model. This image is for reference only.

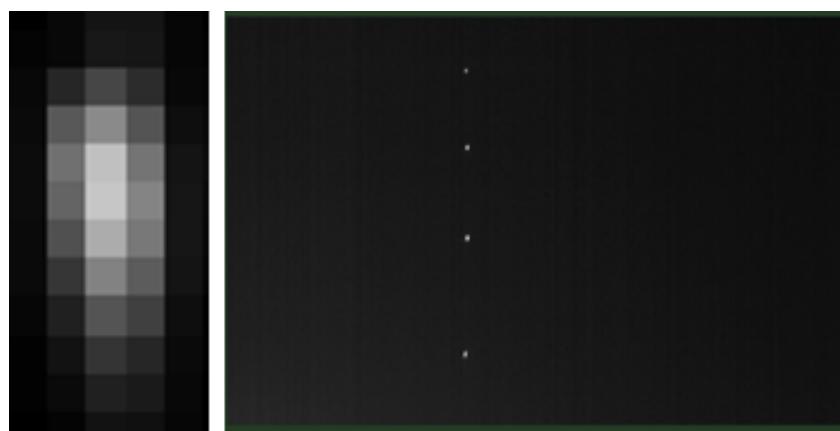


Figure 5-4 Left: Close up example of a blob corresponding to a narrow-band feature. Right: Example of a series of blobs observed with an isolated narrow-band feature acting as the light source. Note that the height, width, and aspect ratio will vary between spectrometer models and wavelengths within the same model. This image is for reference only.

A minor realignment is sometimes required after shipment. Moreover, it is very likely that a new calibration will be needed, even if you do not rotate the grating initially. The instructions for the alignment check and optimization are described below.

NOTICE

The spectrometer has two inputs combined into a single path by a cube beam combiner:

- Single mode fiber (SMF) input: principally used for characterizing laser sources and for the Single-wavelength calibration.
- Multimode fiber (MMF) input: principally used for Broadband calibration or extended source measurements (e.g. plasmas).

For the calibration procedure to be successful, the two inputs (i.e. the tip of the internal SMF and the slit to which the MMF is butt-coupled) must be at equivalent positions horizontally with respect to the collimating lens. **You may be required to perform this procedure upon receiving the unit, and you should verify it regularly .**

Procedure:

1. Launch the SpectraLoK software and select the camera in the **Main Window**.
2. Open the **Camera Window**.
3. Connect a single-wavelength source to the spectrometer's SMF input using a single mode fiber. In the IMAGE CONTROL panel, set the gain to maximum and the exposure time to 200 ms. Typically, the power of the light source should be on the order of uW or mW.
4. Slowly rotate the grating stage until you see a series of blobs. Continue rotating the grating stage until the blobs are roughly in the center of the screen. You should now see a series of over-saturated blobs. Reduce the gain and exposure until the blobs are no longer over-saturated. **Note:** since the range of wavelengths displayed on the sensor at any given grating position is limited, it is important to ensure that the signal is not missed due to overly-rapid tuning of the grating.
5. Use the adjustment knob of the focusing stage (see Figure 5-6) if the laser blobs are not sharp. The resulting blobs should look similar to Figure 5-4.
6. If the blobs with the strongest intensity are not the central ones (i.e. if the vertical intensity envelope is skewed significantly towards the top or the bottom of the sensor), use the vertical adjustment knob of the SMF fiber tip (see Figure 5-5) to center the intensity envelope. You may need to unlock a locking screw. **Note that this step is not typically required, unless the alignment has changed during shipment.** The knob circled in yellow can be used to adjust the vertical intensity envelope of the MMF input, and the knob circle in green can be used to adjust the vertical intensity envelope of the SMF input.
7. Right click on the center of one of the brighter blobs and make a note of the pixel positions (X, Y).

NOTICE

Recall that you can right click any point within the Camera Window to display the pixel coordinates (X, Y) and the individual pixel level corresponding to the camera bit depth. The pixel information is displayed in the bottom right corner of the Camera Window. When you hover over a pixel, the same information is presented in the box in the upper left corner of the Camera Window.

8. Disconnect the single-wavelength source from the SMF input, and then connect it to the MMF input. You should observe a spot at roughly the same position as the spot was when the source was connected to the SMF input. Adjust the gain and exposure until the spot is clearly visible but not over-saturated.
9. Right click on the center of the spot:
 - a. If the spot is within 2 pixels of the spot position obtained with the SMF input, the two inputs are well aligned with respect to one another. This ends the procedure.
 - b. If the difference in position is greater than 2 pixels, go to the next step.
10. Remove the top cover, put gloves on, and adjust the horizontal position of the tip of the internal MMF to make the two inputs coincide, as described in Figure 5-5.

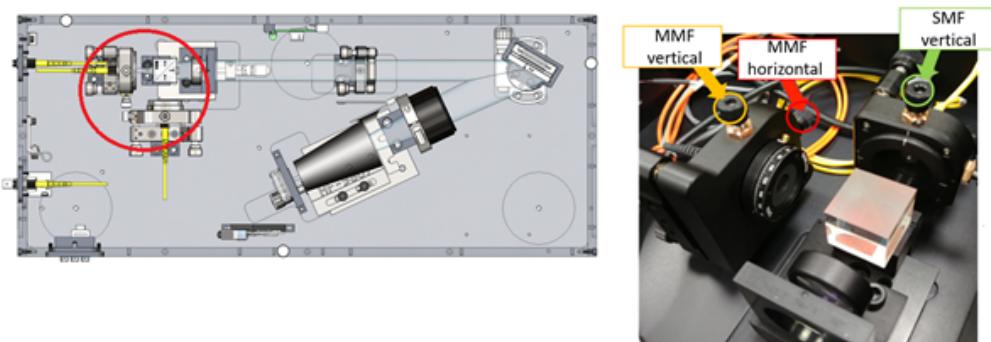


Figure 5-5 Left: Typical location of fiber tip adjustments. Right: Close-up of the adjustment knob that must be used to move the MMF fiber tip in a horizontal direction such as to make the two inputs coincide horizontally (knob circled in red).

NOTICE – vertical adjustment knobs to adjust the vertical intensity envelope

The vertical adjustments of the fiber tips change the height of the light beam incident onto the etalon, altering the average signal intensity and the signal uniformity – since it shifts the center of the vertical intensity envelope onto the sensor.

You should not need to adjust the vertical adjustments of the fiber tips on a regular basis, if at all; you should adjust them only if the signal intensity

is lower than expected or if the intensity profile is far from being centered.

11. Repeat steps 7-10 until the two inputs coincide.
12. Connect a broadband light source to the spectrometer using a multimode fiber and the MMF input. (Typically, a broadband source such as an LED or a tungsten lamp is provided with your spectrometer, together with a multimode fiber).
13. In the Camera Window, set the gain to maximum and the exposure time to 1000 ms. Click **capture background**, then turn the broadband source on, and click **capture**.
14. If you can't see a series of stripes across the camera view, increase the exposure time to 5000 ms seconds and increase the Software Gain. If you still can't see the stripes, check your fiber connection. If there are still no stripes, please contact LightMachinery. They should look similar to Figure 5-3.
15. If the vertical intensity envelope of the stripes is not roughly centered, use the vertical adjustment knob of the MMF fiber tip (see Figure 5-5) to center it. You may need to unlock a locking screw. **Note that this step is not typically required, unless the alignment has changed during shipment.**

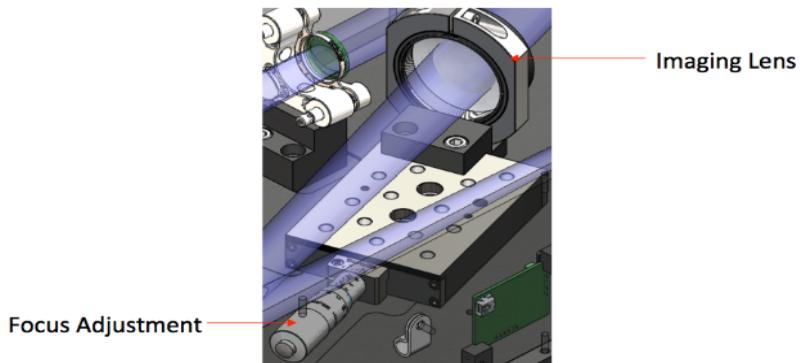


Figure 5-6 Focus adjustment of the imaging lens. Note that there are different types of imaging lenses in LightMachinery units. In most cases it is mounted on a translation stage which must be used to adjust the focus. In all cases, if there is a zoom ring, be sure not to adjust it.

NOTICE – Focus adjustment of the imaging lens

Typical procedure to adjust the imaging lens focus:

1. Carefully remove the spectrometer's top cover and set it aside.
2. Connect a monochromatic laser source using the provided SMF fiber optic cable.
3. Launch the SpectraLoK software and open the **Camera Window**.
4. Enable **capture** to provide a live feed of the input source.
5. Zoom on one of the blobs.
6. Locate the imaging lens and adjust focus while watching the **Camera Window** (*Do not adjust the zoom ring*). Continue adjusting the focus until the image spot appears clear and well defined (**prioritize minimizing the horizontal width of the spot**). In general, a few degrees turn is required to optimize the focus. If the lens is on a translation stage, try quarter turns of the micrometer at first.

After completing the initial installation, the imaging lens focus should only be adjusted if the grating angle is changed significantly (resulting in a change in the wavelengths incident on the camera of more than 20nm), or if there is a significant amount of FSR crosstalk observed in the unwrapped spectrum. Adjusting the focus of the imaging lens alters the size and position of the light source's blobs and stripes. Therefore, a **Full Calibration** must be completed before taking any further spectra.

Section 6 - Calibration

NOTICE

Appendix A describes the principles of operation of the LightMachinery spectrometers and the theory behind the calibration process. Please read Appendix A before carrying out any of the calibration processes described below.

This section describes two different calibration processes – the **Full Calibration** (in which both the etalon and grating dispersions are calibrated) and the **Quick Calibration** (which corrects any small instrument drifts). The **Full Calibration** is initially carried out at LightMachinery when the instrument is first assembled; once the **Full Calibration** is completed, carrying out the **Quick Calibration** procedure compensates for any small changes in stripe position on the sensor.

ATTENTION

The Full Calibration procedure must be carried out whenever significant alignment changes have occurred in the instrument (possibly after shipment, for example), or the grating has been rotated (for units with a rotatable grating). If you receive your spectrometer and are unsure if it requires calibration, please contact LightMachinery.

The Quick Calibration procedure (or alternatively a manual adjustment of the LUT Horizontal Offset) should be performed regularly, namely whenever a small drifts in the experimental stripe positions occur due to changes in temperature, minor mechanical drifts, or movement of the input fibers (including disconnection/ reconnection). At the beginning of the day, and possibly a few times through the day, the user should verify the stripe overlay in the camera window (see Figure 6-3) and a Quick Calibration should be carried out if the mismatch reaches >1 pixel.

6.1 Full Calibration

The **Full Calibration** procedure consists of two procedures: The **Etolon Calibration** followed by the **Grating Calibration**. Each procedure calibrates one of the two orthogonal axes of the spectrometer.

Two different light sources are required for the calibrations:

Narrowband source

An etalon disperses the light in the vertical direction. To calibrate the etalon dispersion, a light source with one or more narrowband spectral features within the wavelength range captured by the sensor is required. The narrowband source can be a single-mode laser, a multimode laser (with distinct, separate features), or a spectral/arc lamp with narrowband features. Ideally, the narrowband spectral features will have a line-width less than the resolution limit of the spectrometer (typically between 1 and 25 pm, depending on the model). At the very least, the narrowband source **must** be significantly narrower than the etalon FSR (typically between 30 and 2000 pm, depending on the model). LightMachinery can suggest suitable calibration sources – please contact us for details.

NOTE

The reference wavelengths for most narrowband sources (lasers or lamps) are given in terms of the wavelength as measured in a standard atmosphere of AIR. If the calibration process is carried out using reference air wavelengths, then SpectraLoK reports all wavelengths as measured in air. To convert from these air wavelengths to wavelengths as measured in VACUUM, multiply the measured value by 1.000278.

Broadband source

A diffraction grating disperses the light in the horizontal direction. To calibrate the grating dispersion, a broadband spectral source is required. This source should provide “white light” (a relatively uniform intensity versus wavelength spectrum) over the range of wavelengths that fall onto the camera sensor. Typically, a broadband source such as an LED or tungsten lamp is provided with your spectrometer.

NOTICE

If your spectrometer came with specific calibration instructions (see your Custom Instructions), then use them in place of the following instructions.

NOTICE

If it is the first time that you are operating the spectrometer, **load the configuration file** from the Main Window (under FILE I/O). Select the original configuration file when prompted.

6.1.1 Pre-Calibration

1. Make sure that the USB cable(s) connecting the spectrometer (and the external camera, if applicable) to your computer is plugged into an available USB 3.0 port or better, the DC power supply is connected, and the correct camera is selected in the Main Window.

2. Make sure that you have read the instructions regarding connecting a light source to the spectrometer in Section 5 of this manual, and have prepared the necessary fiber optic cables.
3. Make sure that your input light source is properly aligned (See Alignment Check in Section 5) and that you have carried out the Alignment Checks and Optimization procedures (Section 5.3) relevant to your model.

6.1.2 Etalon Calibration

1. Connect the narrowband source to the MMF spectrometer input port.
2. Open the Camera Window and click the **Capture** button. Typical sensor images obtained with a narrowband source are shown in Appendix C. Identify the series of “blobs” that you plan to use for the etalon calibration, as illustrated in Appendix C. In general, choose a series of blobs that clearly belong to the same spectral feature; each blob should have minimal extent in the vertical direction and be correctly exposed (see next steps). The wavelength of the selected spectral feature must be known to allow accurate calibration of the wavelength scale of the spectrometer (an accuracy of significantly better than 1% in the wavelength of the narrowband source is required for accurate calibration of the wavelength scale).
3. Make sure that the power of the narrowband source is suitable for the calibration, and then optimize the exposure and gain while avoiding saturation of the sensor pixels. See Appendix E for further details.
4. Once the intensity levels of the chosen series of blobs have been optimized, click **Stop** to prevent further updating of the image.
5. Now select all the blobs in the series by drawing a rectangular box around each blob in turn (Hold the Control key and then right click and hold while on the center of each blob. Drag a rectangle around each blob before releasing the mouse button. Alternatively, if the blobs are reasonably isolated in the Camera Window, simply right click on each blob in turn. The “Box width and height” must be set to an appropriate value to ensure that only a single blob is contained within the selected square). Each rectangle should encompass all the pixels containing intensity associated with the blob but should not include any pixels containing intensity from nearby spectral features. Examples are shown in Appendix C. **Select each blob once only and select at least 3 blobs in sequence.**
6. In the Settings Window, go to the **Etalon Calibration** Window and check that the **Use Current Image** slider is enabled.
7. Click **Calibrate Etalon** and confirm that the wavelength value is correct. At this stage, the software examines each selected area in turn, and determines the (X, Y) pixel coordinates for the center of each blob (all pixels outside the selected rectangles are ignored). The software then compares these experimental positions with those predicted by the model, determines the difference between the experimental and predicted Y-positions, and then varies the model parameters to minimize the sum of (differences)². Once a good fit is obtained between the experimental blob positions and the predicted blob positions, the software reports the results in both graphical and numerical form. Figure 6-1 shows typical screenshots after a successful **Etalon Calibration**.

8. Optional: Disable **Use Current Image** and then click **Etalon Calibration** again. The software will carry out another “best fit” procedure on a new image and report the results. You will notice minor changes in the fit from image to image as the exact position of the experimental blobs varies. However, if the source is unstable and shifts in wavelength, the blobs may move outside of the selected rectangles, and the calibration will fail.
9. **For calibrating low level light sources by manually selecting points, see Appendix D.**
10. Before proceeding to the next step, compare the reported value of the Least Squares Deviation, LSD, and the maximum deviation of any blob (see graph) with the vertical extent of a typical blob. The LSD should be <10% of the vertical extent of the blobs, and the maximum deviation should be <30%. For example, if the blobs are roughly 10 pixels in vertical extent, the LSD should be <1 pixel, and the centres of all blobs should not deviate by more than 2-3 pixels from the predicted position.
11. Once a good fit is obtained between the calculated and experimental blobs, click **save configuration** to save the calibration settings to the configuration file. (This will overwrite the existing configuration file. Click **save as** in the Main Window or Settings Window if you want to create a new configuration file).
12. Perform the **Grating Calibration** to complete the **Full Calibration** procedure.

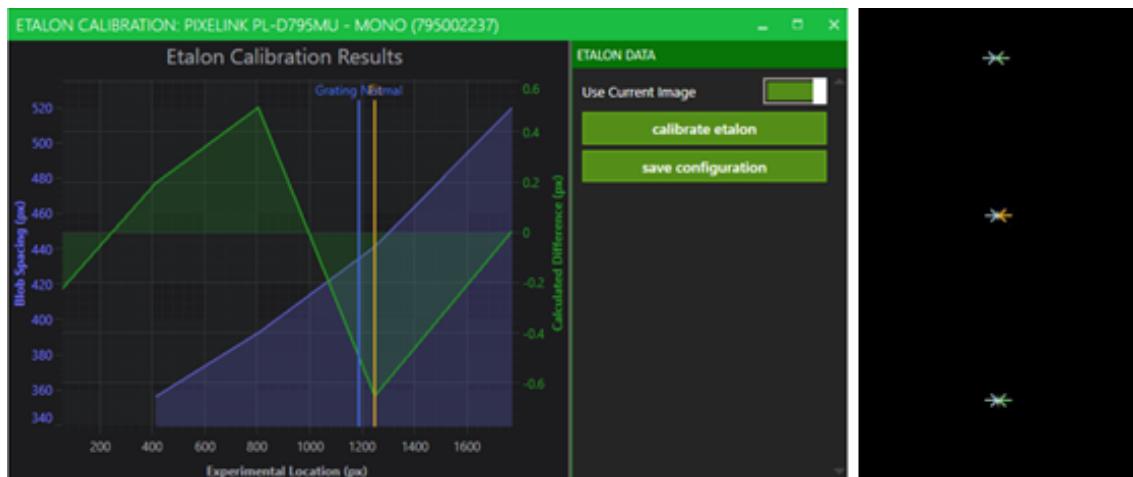


Figure 6-1 Screenshots after a successful Etalon Calibration using 5 blobs.

As indicated by the right-hand vertical axis of the graph in Figure 6-1, note that the maximum deviation between the predicted and the experimental blob positions is <30% of the vertical extent of the blobs. The cursors on the graph show where the normal to the grating intersects the sensor (blue cursor), and the position of the closest blob that is used as the reference for the unwrapping process (orange cursor). In the right image of Figure 6-1, the overlay “Etalon Peaks (V)” illustrates the blob centroids and the fit to three of the blobs in the Camera Window. The blob with the maximum deviation from the predicted position is indicated by the orange arrow.

6.1.3 Grating Calibration

1. Connect the Broadband source to the MMF spectrometer input port.
2. Open the Camera Window and enable **Capture**.
3. The key to a successful **Grating Calibration** is to ensure a good signal-to-noise ratio in the stripes image. See Appendix E (Weak Light Sources) for the appropriate procedures. In all cases, the use of Background Subtraction is strongly recommended, as described in Appendix E.
4. Once a good set of stripes have been obtained, click Stop to freeze the image.
5. Go to the Settings Window and ensure that the unwrapping ROI is set to the same values as in your original Configuration file (this ensures that the LUT generated by the calibration process encompasses the maximum useful area on the sensor).
6. Hit the “**reset quick calibration**” button to return the predicted stripes to the positions determined by the most recent **Grating Calibration**.
7. In the Settings Window, go to the Grating Calibration Window and ensure that the Use current image slider is enabled.
8. Click **Calibrate Grating**. The software determines the X-position of all the peaks of the experimental stripes in a “slice” across the sensor (there are usually ~100 stripe peaks). The software then compares these experimental positions with those predicted by the model, determines the difference between the experimental and predicted X-positions, then varies the model parameters to minimize the sum of (differences)². Once a good fit is obtained between the experimental and the predicted stripe positions, the software reports the results in both graphical and numerical form. Figure 6-2 shows a typical screenshot after a successful **Grating Calibration**.
9. Optional: Disable **Use current image** and then click **Calibrate Grating** again. The software will carry out another “best fit” procedure on a new image and report the results. You will notice minor changes in the fit image to image as the exact position of the experimental stripes varies. This procedure may take a minute or two, as a new image must be acquired (including the averaging of several exposures, if selected).
10. Before proceeding to the next step, compare the reported value of the Least Squares Deviation, LSD, and the maximum deviation of any stripe (see graph) with the typical stripe separation. The LSD should be <20% of the stripe separation, and the maximum deviation should be <40%. For example, if the average stripe separation is 30 pixels, the LSD should be <6 pixels, and the peak position of any stripe should not deviate by more than 12 pixels from the predicted position.
11. Once a good fit is obtained between the calculated and experimental stripes, ensure that the “Use current image” slider is enabled, and then click on the **calculate ICE and correct stripes** button. Confirm that a broadband image is captured and wait a few minutes as the software improves the fit of the predicted stripe overlay relative to the experimental stripes. (The software also automatically calculates and stores the parameters required to carry out an Intensity Correction and Envelope correction, ICE correction. These parameters will be used whenever the ICE correction is enabled in the Settings Window).
12. Finally, click **save configuration** in the Settings Window to save the calibration settings to the configuration file. (This will overwrite the existing configuration file. Click **save as** in the Main Window or Settings Windows if you wish to create a new configuration file).

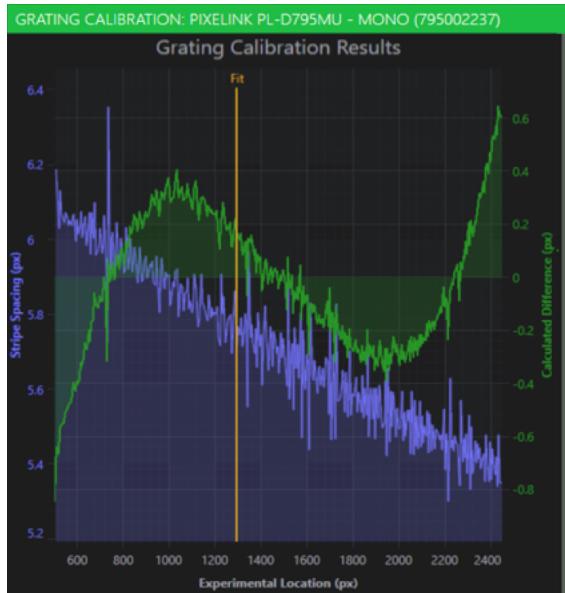


Figure 6-2 Screenshot after a successful Grating Calibration.

As indicated by the right-hand vertical axis in Figure 6-2, the maximum deviation between the predicted and the experimental stripe positions is only ~0.7 pixels. The cursor shows the X-position of the blob that is used as the reference for the unwrapping process.

The **Full Calibration** procedure is now complete, and the parameters used in the model have been optimized to predict the positions of all the experimental stripes within the Unwrap area on the sensor. As a final calibration check, in the Camera Window enable the Overlay **Stripe Overlay (S)** and compare the experimental and predicted stripe positions across the entire sensor. The fit is usually good to a pixel or two within the entire Unwrap area. Figure 6-3 gives an example of the fit between the experimental stripes and the predicted stripe positions.

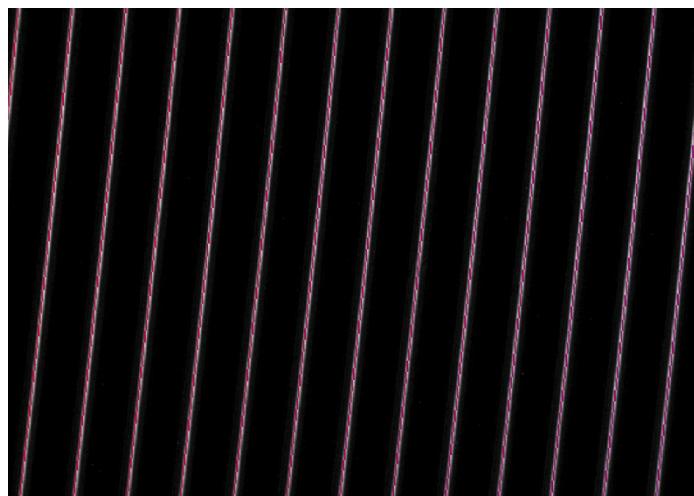


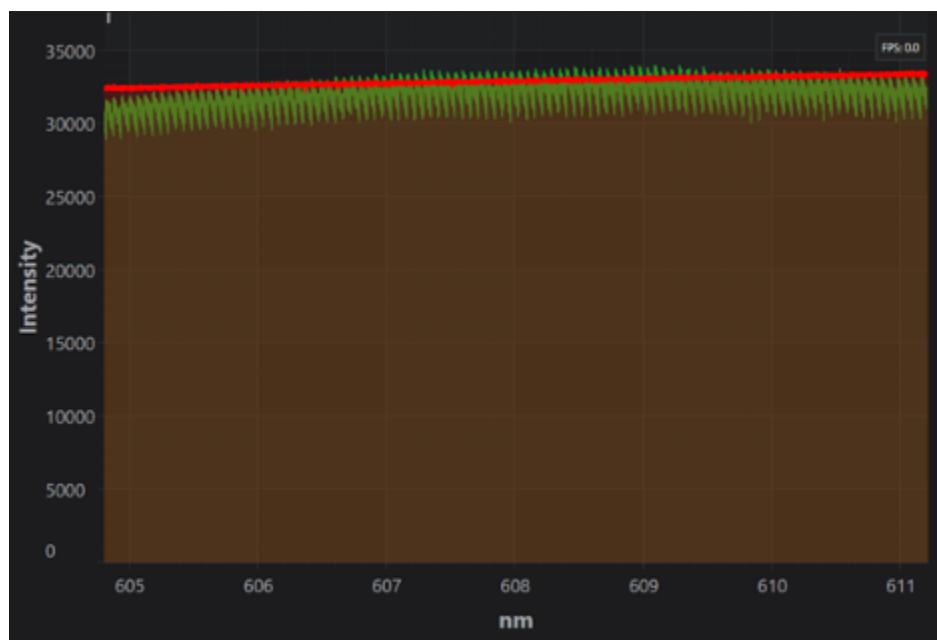
Figure 6-3 Screenshot showing experimental stripes with “Show Stripe Overlay” enabled. Note the alignment of the coloured overlay and the centres of the experimental stripes (shown in white behind the colour overlay). Only a portion of the sensor is displayed.

6.2 Intensity Axis Calibration using the ICE corrections

The calibration procedures described in Section 6.1 are designed to accurately calibrate the wavelength axis (X-axis) of the Spectrometer. The intensity axis (Y-axis) of the spectrometer may also require calibration, and this is handled by the ICE corrections.

In any spectrometer, several factors can affect the intensity axis calibration such that the displayed spectrum does not accurately reflect the intensity-versus-wavelength properties of the input light. These factors include the sensor wavelength sensitivity, the variation in grating efficiency with wavelength, differences in optical transmission at the edges of the sensor relative to the middle, wavelength-dependent variations in the transmission and reflection of the optical components in the spectrometer, etc. Fortunately, there is no need to separate out the different contributions to the variation of the intensity axis with wavelength –the combined effects can be corrected by a single calibration using a light source with a **known** variation of intensity with wavelength. Black-body radiation from an incandescent filament satisfies this requirement. (Details can be found at https://en.wikipedia.org/wiki/Black-body_radiation). Hence, provided the temperature, T, of the incandescent-filament light source is known, the variation in intensity with wavelength for any wavelength range in a spectrometer can be determined, and the intensity axis calibrated.

If an incandescent lamp provided by LightMachinery is used as the broadband source for the Grating Calibration described in Section 6.1.3, then the correction coefficients for the intensity axis are automatically calculated when the **calculate ICE and correct stripe** button is clicked. The effect of the ICE corrections can be observed by checking and unchecking the **Enable ICE** box in the Settings Window (and clicking on the **calculate stripe overlay** button whenever a change is made). Figure 6.4 compares the spectral unwrap of such a lamp with and without the ICE corrections enabled.



*Figure 6-4 Screenshot of the spectrum of an incandescent-filament light source with (red) and without (green) the **enable ICE** box checked in the Settings Window. The modulation on the green trace has a period that equals the FSR of the internal etalon / VIPA of the spectrometer.*

Note that ICE correction removes the modulation that occurs when adjacent stripes are stitched together, but also corrects the baseline level to reflect the relative values expected for an incandescent-filament light source in this wavelength region.

6.3 Quick Calibration

The **Full Calibration** procedure is carried out at LightMachinery immediately before each spectrometer is packed for shipping. The optimized model parameters are saved in a unique Configuration File that must be loaded onto any computer using the SpectraLoK software. As each model parameter corresponds to an unchanging physical property of the spectrometer (such as etalon thickness or imaging lens focal length), we have found that the fit of the experimental stripes (as indicated by the Overlay “Stripe Overlay (S)”), remains almost unchanged over long periods of time, *provided no adjustments are made to the alignment of the optical components*. However, the model cannot accurately predict the stripe position after the focus of the imaging lens is adjusted, the etalon tilt is changed, or the grating is rotated (some models only).

Small drifts in the experimental stripe positions may occur due to changes in temperature, minor mechanical drifts in the optical mounts, or movement of the input fibers. If the difference between the predicted and experimental stripe positions approaches a significant fraction (e.g. >20%) of the stripe separation, the spectral unwrapping process will lead to suboptimal results and it may even fail. The **Quick Calibration** procedure resets the predicted stripe positions to the new experimental stripe positions if any drift has occurred. It should be performed before the difference between the predicted and experimental stripe positions approaches 50% of the stripe separation, otherwise the **Quick Calibration** procedure will fail or it will lead to incorrect results.

To perform the **Quick Calibration**:

1. Connect the experimental light source to the appropriate spectrometer input port. (typically carried out with the light source under investigation).
Open the Camera view, click **Capture**, and then adjust the exposure and gain settings to optimize the signal displayed by the camera so that the image is just below saturation

NOTICE

In certain models where the natural background level of the camera is high, it is necessary to acquire a background image (with the exposure and gain settings found in step 2) before proceeding to step 3.

2. Enable the **Stripe Overlay** (hit S on the keyboard) and note the offset between the predicted stripe positions (coloured) and the stripes/blobs from the light source (grey/white).

3. In the Settings Window, click **Quick Calibration**, this can take up to a minute or two.. **If the Quick Calibration calculation determines that the required change to the stripe overlay position is less than 0.1 pixel, no correction is applied.** On the other hand, If the stripe overlay does not agree exactly with the experimental stripes/blobs, click on the **Quick Calibration** a second time.
4. Optional - once the automated Quick Calibration is complete, the exact position of the stripe overlay can be manually “fine-tuned” using the “LUT horizontal offset” parameter in the Settings Window. Be sure to “calculate stripe overlay” after each change to the “LUT horizontal offset” parameter (this ensures the LUT is properly updated).
5. All future spectral unwrappings and stripe overlay calculations will include the offsets determined by the **Quick Calibrations** procedures. To return to the original stripe positions (as determined by the most recent **Grating Calibration**), hit the button “reset quick calibration”, followed by the “Calculate Stripe Overlay” button in the Settings Window.

As the **Quick Calibration** procedure takes little time (~ one minute) and is best performed with the light source under investigation, it is recommended that calibration be performed at regular intervals, or whenever the fit between the experimental stripes and predicted stripes has drifted (the relative positions can be observed in the Camera Window at any time).

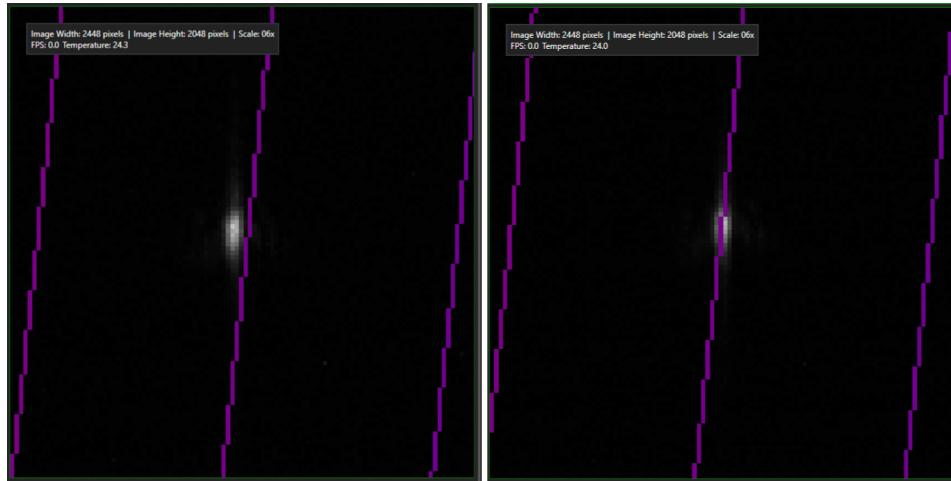


Figure 6-5 Screenshots before and after a Quick Calibration with a narrowband light source. Note the improvement in the fit between the predicted stripe positions and the experimental blobs after the Quick Calibration (right image).

6.4 Calibration using an External Etalon Module

6.4.1 Preparation

1. First ensure that suitable images are available for the calibration process. A total of three images are required, as described below. Each image should be generated and saved before starting the calibration process.
2. The first image is taken with a Broadband source as the input to the spectrometer, and this image will be referred to as the **Stripe image**.

- a. Connect the Broadband source to the spectrometer input port.
 - b. Open the Camera Window and enable **Capture**.
 - c. The key to a good Stripe image is to ensure a good signal-to-noise ratio. See Appendix F (Weak Light Sources) for the appropriate procedures. In all cases, the use of Background Subtraction is strongly recommended, as described in Appendix F.
 - d. Ensure that the Stripe image has sufficient intensity throughout the Region of Interest, ROI, and is not strongly saturated in any regions (slight saturation is OK).
 - e. Once a good set of stripes have been obtained, click Stop to freeze the image.
 - f. Save the image by hitting Ctrl+Shift+S in the Camera Window. Choose a name that makes it easy to recognize the saved image as the Stripe image.
3. The second image is also taken with a broadband source, but the light passes through an external etalon before entering the spectrometer. The transmission peaks of the etalon modulate the stripes and result in a series of dots throughout the image. Hence this image is referred to as the **Dot image, or the Etalon Modulated image**.
 - a. Connect the external etalon module between the Broadband source and the spectrometer input port.
 - b. Open the Camera Window and enable **Capture**.
 - c. The key to a good Dot image is to ensure a good signal-to-noise ratio. See Appendix F (Weak Light Sources) for the appropriate procedures. In all cases, the use of Background Subtraction is strongly recommended, as described in Appendix F.
 - d. Ensure that the Dot image has sufficient intensity throughout the Region of Interest, ROI, and is not strongly saturated in any regions (slight saturation is OK).
 - e. Once a good set of dots have been obtained, click Stop to freeze the image.
 - f. Save the image by hitting Ctrl+Shift+S in the Camera Window. Choose a name that makes it easy to recognize the saved image as the dot image.
4. The final image is used to provide a single point of wavelength reference for the calibration process. Typically, the light source is a narrowband laser or a lamp emitting one or more lines of known wavelength. Alternatively, the wavelength reference may be a HyperCal unit supplied with your spectrometer. With the wavelength reference source input to the spectrometer, the resulting image is generally a series of vertical “blobs”; hence it is referred to as the **Blob image**.
 - a. Connect the wavelength reference source to the spectrometer input port.
 - b. Open the Camera Window and enable **Capture**.
 - c. The key to a good Blob image is to ensure a good signal-to-noise ratio. See Appendix F (Weak Light Sources) for the appropriate procedures. In all cases, the use of Background Subtraction is strongly recommended, as described in Appendix F.
 - d. Ensure that the Blob image has sufficient intensity throughout the Region of Interest, ROI, and is not strongly saturated in any regions (slight saturation is OK).
 - e. Once a good set of blobs have been obtained, click Stop to freeze the image.

- f. Save the image by hitting Ctrl+Shift+S in the Camera Window. Choose a name that makes it easy to recognize the saved image as the Blob image.

Typical Stripe, Dot and Blob images are shown in Figure 6-6

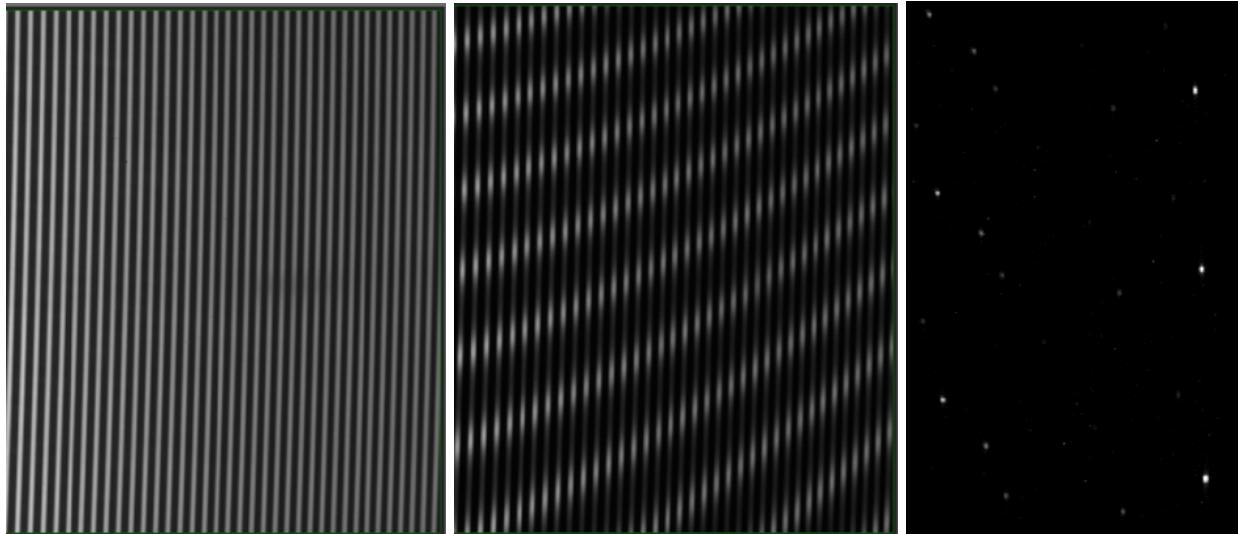


Figure 6-6 – Typical Stripe, Dot and Blob images displayed from left to right.

6.4.2 Calibration

1. Open the “Mapping Calibration” Window (go to the Calibration drop-down menu in the Settings Window and select “Mapping Calibration”).
2. Change to the Camera Window and load the Stripe image that was saved in Section 6.4.1. Type U to display the ROI with pink boundaries. Drag the boundaries to set the ROI as large as possible without including very dark regions. Switch to the “Mapping Calibration” Window and click on the button “**use current image**” next to the Broadband Image. A check mark will appear in the appropriate box.
3. Change to the Camera Window and load the Dot image that was saved in Section 6.4.1. If need be, reduce the ROI to avoid very dark regions in this image. (If either the Stripe or Dot image have major dark regions, retake the images with an increase in exposure time to “fill in” these regions). Switch to the “Mapping Calibration Window” and click on the button “**use current image**” next to Etalon Modulated Image. A check mark will appear in the appropriate box.
4. Change to the Camera Window and load the Blob image that was saved in Section 6.4.1. Identify a single blob of known wavelength within the ROI. Zoom in on this blob and move the cursor to the center of the blob (in both X and Y). Note the X- and Y-position of this central pixel (given under mouse position in top left of screen). Switch to the “Mapping Calibration” Window and enter the reference wavelength, X and Y pixel position into the relevant boxes.
5. With information from all three images entered in the “Mapping Calibration” Window, it is now time to complete the calibration by clicking on the green **execute** button. The software will take a minute or two to execute all the calibration steps and to calculate the results.

6.4.3 Validating and Saving the new Calibration

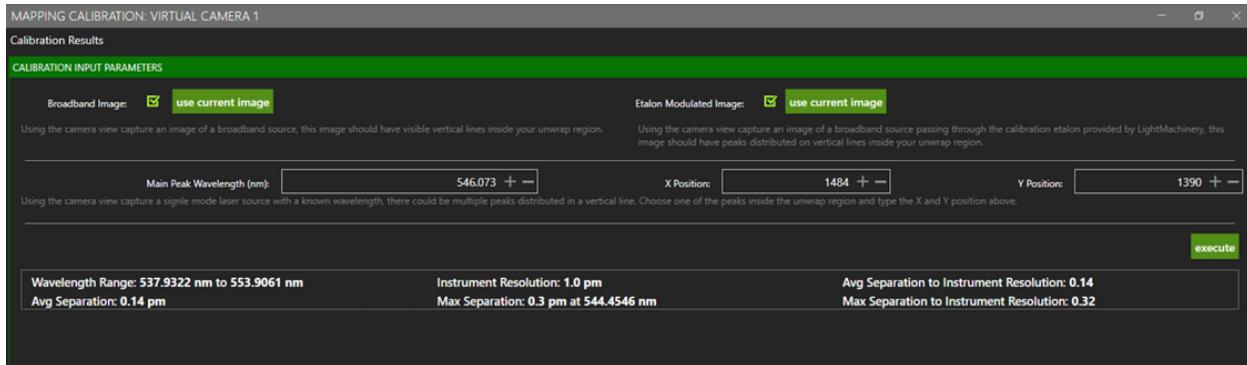


Figure 6-7 Screenshot of the Mapping Calibration Window after a successful calibration.

1. Once the calibration is complete, the software returns six different numbers, as shown at the bottom of Figure 6-7, and described below.
 - a. *The wavelength range of the calibration in nm.* This range is determined by the values of the minimum and maximum X-pixels in the ROI.
 - b. *The average separation in pm.* Each transmission peak of the external etalon has a unique wavelength, but if the ROI contains 5 vertical orders (for example), then 5 different dots will nominally correspond to this same wavelength, spread out over the vertical height of the ROI. The software calculates the wavelength of each dot and determines the difference between the maximum and minimum wavelengths. This difference is called the **separation** and is generally a small fraction of the nominal resolution of the spectrometer. The average value of the separation for all the etalon peaks is one of the results reported by the software. A more detailed description of the **separation** can be found in Appendix B2 (specifically Figures 10-13 and 10-14).
 - c. *Instrument Resolution in pm.* This number is the nominal spectrometer resolution (usually specified at the middle of the wavelength range of the spectrometer), as entered in the Configuration File at LightMachinery.
 - d. *Maximum separation in pm, together with the wavelength at which it occurs in nm.* The wavelength tells us where there is maximum separation between the etalon peaks from adjacent stripes. The calibration is the worst at this wavelength.
 - e. *Average separation to instrument resolution.* The ratio of the average separation (typically measured over >100 peaks) to the nominal instrument resolution. This ratio is usually <0.5 for a good calibration.
 - f. *Maximum separation to instrument resolution.* This number represents the “Figure of Merit” for the calibration. If the value is <1.0, the calibration is good even in the worst case, and no significant loss of resolution will occur at any wavelength. If the number is >1.0 but <3.0, the number is displayed in yellow. There may be a slight loss of resolution at some wavelengths. If the number is

- >3.0, the number is displayed in red, and there may be a problem with the calibration. Please contact LightMachinery.
2. If the results of the calibration are satisfactory, you are ready to generate a new Configuration File with all the new calibration information. At this stage, it is a good idea to use “Save As” in the Settings Window to generate a new Configuration File and hence preserve the original Configuration File. After this step, go to the “Mapping Calibration” Window, click “Calibration Results” (top left corner) and “Save to config file” from the drop-down menu. This step may take a while, as the software is saving >50 Mb of data. (In the future, if you wish to remove all the new calibration information from the Configuration File, click “Calibration Results” / “Clear from config file”).
 3. The calibration process is now complete.

6.4.4 Intensity Axis Calibration (when using the external etalon module calibration process).

As part of the “Mapping Calibration” process, the software also carries out two different procedures to calibrate the Intensity Axis of the displayed spectra. First, the software ensures that there are no “stitching errors” when the spectra from adjacent stripes are combined. These “stitching errors” can cause modulation in a broadband spectrum with a period equal to the FSR of the etalon or VIPA that is internal to the spectrometer. In addition, the software corrects the intensity as a function of wavelength to ensure the displayed spectra agrees with the known spectrum of the broadband source (generally a tungsten filament with a blackbody temperature of ~3000 K). This second correction accounts for any grating and sensor efficiency variations across the recorded wavelength range.

The corrections to the Intensity Axis can be turned on and off by going to the Settings Window and checking (or unchecking) the box labeled **Enable ICE**, followed by **calculate stripe overlay**. It is a good idea to unwrap the Stripe image with and without the Ice correction to observe the effect of the intensity corrections -see Figure 6.4 for an example. (It is generally recommended to take spectra with the box **Enable ICE** checked).

6.5 Troubleshooting

6.5.1 Etalon Calibration

If the **Etalon Calibration** fails, or if the maximum deviation between the predicted and experimental blob positions exceeds ~30% of the vertical blob extent, try the following steps:

1. Check for error messages at the bottom of the SpectraLoK Window.
2. Check that you have selected at least three blobs from the same series, and have selected the blobs in order.
3. Ensure that the blobs are not saturated, nor have very little intensity.
4. Ensure that the selected blobs have a vertical extent that is significantly smaller than one etalon FSR.
5. Confirm that the wavelength is entered correctly.
6. Repeat the **Etalon Calibration**.
7. If the **Etalon Calibration** is still unsuccessful, load the original configuration file generated at LightMachinery and repeat Steps 2 through 6.
8. If the Etalon Calibration fails after several attempts, please contact LightMachinery.

6.5.2 Grating Calibration

The main cause of a **Grating Calibration** failure is poor stripe quality. Complete the following steps to maximize the stripe quality (always check for error messages at the bottom of the SpectraLoK Window):

1. Follow the steps described in Appendix E (weak sources) to optimize the stripe signal on the sensor (Background Subtraction, Signal Averaging, and setting both the exposure and gain for the best signal).
2. Ensure that the focus of the imaging lens is optimized (see Section 8).
3. Once the optimum stripe signal is obtained in the Camera Window, enable **Use current image** in the **Grating Calibration** Window before clicking **Calibrate Grating**.
4. If the **Grating Calibration** is still unsuccessful, load the original configuration file generated at LightMachinery and repeat Steps 1 through 4.
5. If the **Grating Calibration** is still unsuccessful, use a more intense broadband source and repeat steps 1 through 5.
6. If the **Grating Calibration** fails after several attempts, please contact LightMachinery.

6.5.3 Intensity Axis Calibration

If you can't get a good signal for any of the calibration procedures above:

1. Clean fibers.
2. Ensure that you are using a SMF or a small core MMF if the spectrometer has no slit;
3. Ensure that you are using a large core MMF (typically 200 um) if the spectrometer has a slit;
4. Ensure that you are using a long-pass filter if your central wavelength is >800nm;
5. Ensure that your exposure and gain are not so high that it saturates (always check the signal you get before subtracting the background for a given exposure and gain);
6. Use up to several minutes of averaging if required;
7. Ensure that the alignment (in particular the focus) is optimal. This is often easier to verify with a narrowband source.

6.5.4 Quick Calibration

If the **Quick Calibration** procedure does not produce an improvement in the fit between the predicted stripes and the light source intensity on the sensor (similar to the improvement shown in Figure 6-4), try the following:

1. The **Quick Calibration** procedure looks at all the light hitting the sensor in the selected ROI and emphasizes the pixels with the maximum intensity in the entire ROI. Reduce the extent of the ROI to limit the correction to the wavelengths under study.
2. Use background subtraction.
3. Consider manually “fine-tuning” the “LUT horizontal offset” parameter in the Settings Window.

6.5.5 Mapping Calibration

The main cause of a Mapping Calibration failure is poor quality of the dot image (or more rarely the stripe image). Complete the following steps to maximize the quality of the dot and stripe images (always check for error messages at the bottom of the SpectraLoK Window):

1. Follow the steps described in Appendix F (weak sources) to optimize the dot and stripe signal on the sensor (Background Subtraction, Signal Averaging, and setting both the exposure and gain for the best signal).
2. Ensure that the focus of the imaging lens is optimized (see Section 8).
3. Once the optimum dot or stripe signal is obtained in the Camera Window, save the image for use in the Mapping Window.
4. If the Mapping Calibration is still unsuccessful, try to use a more intense broadband source and repeat steps 1 through 3.
5. If the Mapping Calibration fails after several attempts, please contact LightMachinery.

Section 7 - Operation

This section contains step-by-step instructions on how to obtain spectral measurements using the SpectraLoK software, including techniques to optimize the measurements for a variety of applications.

7.1 Acquiring a Spectrum

CAUTION

Ensure that you have completed the spectrometer installation and calibration before proceeding with any of the following operations. Note that fixed grating units come pre-calibrated.

ATTENTION!

When the SpectraLoK software is launched, only the SpectraLoK window is initially displayed. Select the correct camera sensor, click the Camera Icon, and then click **Capture** to display a live feed of the image on the sensor in the Camera window. To access the Spectrum Window, click on the Spectrum Icon in the SpectraLoK Window or use the Windows Menu of the Camera Window.

ATTENTION!

Follow the instructions in Section 5 to connect a light source to the spectrometer.

Take a spectrum reading

NOTICE

If your spectrometer came with specific instructions for measuring spectra (see Custom Instructions), then use them in place of the following measurement instructions.

1. Connect the spectrometer to your computer using the USB 3.0 cable and launch the SpectraLoK software.
2. Connect your light source to the spectrometer's input port using a fiber optic cable (see instructions in Section 5).
3. If this is the first time this light source has been connected, it is recommended to perform a **Quick Calibration** (see Section 6).
4. In the Spectrum Window, click **Unwrap** to display a live feed of the spectrum.

5. Double-click the left mouse button to see the entire spectrum, or left-click on “**Display Full Range**”.

The spectrum of the input light source should now be displayed in the Spectrum Window. To help with the optimization of the displayed spectrum, see “Optimizing the Spectrum Display” below.

7.2 Optimizing the Spectrum Display

Several steps can be taken to optimize the Spectrum display. These steps are outlined in the following instructions.

7.2.1 Optimize the Exposure and Gain

For most applications, the exposure and gain are optimized when the most intense spectral feature in the signal is just below the saturation level of the sensor. The optimum exposure and gain are easiest to set in the Camera Window, after enabling the **EFFECTS CONTROL** slider to display any saturated pixels in colour, as shown in Figure 7-1. It is desirable to avoid saturation since saturation often compromises the linearity of the intensity scale.

ATTENTION!

The presence of saturation is often not obvious when viewing the spectrum in the Spectrum Window, due to the smoothing and averaging involved in the unwrapping process. In other words, you will rarely see a saturated plateau in the Spectrum Window corresponding to the maximum level - 4095 for a 12-bit sensor - even if some of the pixels are saturated.

It is important to avoid saturation of the features of interest to prevent distortion of the spectral features and to minimize FSR crosstalk, which can increase significantly in the presence of saturation.

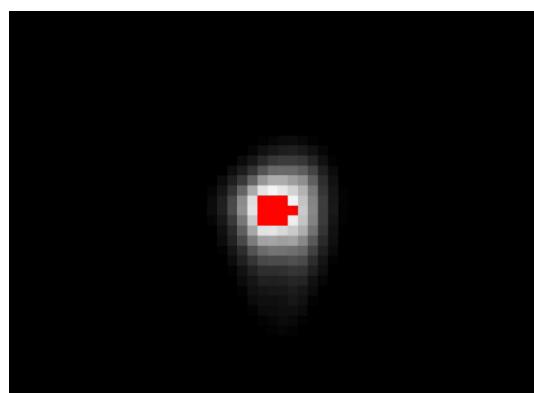


Figure 7-1 Screenshots of a blob with saturated pixels. (The EFFECTS CONTROL slider is enabled).

Initially, increase the exposure until a few pixels start to saturate. Check that the saturated exposure level corresponds to the maximum level of the camera sensor (4095 for a 12-bit sensor). Reduce the exposure to eliminate any saturated pixels (or the majority of saturated pixels). *For optimal signal stability, it is best to use longer exposures in combination with a lower gain, rather than short exposures with high gain.*

Over-saturated blobs can also be observed in the unwrapped spectrum. Once “Internal Saturation Detection” is enabled in the Spectrum Window, wavelength bins containing pixels over the set intensity limit will show as red on the unwrapped spectrum.



Figure 7-2. Screenshot of a spectrum taken with the toggle “Internal Saturation Detection” enabled. All wavelength bins that contain pixels over the set intensity limit (prior to background subtraction, if applicable) are displayed in red. Note that the saturated portions of the spectrum shown in red are not smoothed (hence they typically do not have the same intensity as the underlying green spectrum).

In some applications (Brillouin and Raman spectroscopy, in particular) it is common to have a pump laser that strongly saturates the sensor in a limited region. For these applications, the goal is to ensure that the Brillouin or Raman signal does not cause saturation. Additional information on optimizing the exposure and gain can be found in Appendix E. Ideally, the Raman excitation wavelength is kept just out of the range of the observed window. An edge filter should be used when only examining Stokes scattering, or a notch filter for both Stokes and anti-Stokes scattering.

NOTICE

Appendix B1 describes the theory behind the unwrapping process, gives a description of the physical model used in unwrapping, and explains the

concept of the Look Up Table, LUT. Please read this Appendix before attempting to optimize the unwrapping parameters. **Your original configuration file contains unwrapping parameters that have been optimized for typical applications of your spectrometer.**

ATTENTION!

When adjusting the parameters discussed in Sections 7.2.2 through 7.2.5 below, it is essential to first STOP any continuous unwrapping of the spectrum, make the change to the relevant parameter, hit “**calculate stripe overlay**”, and then restart the unwrapping process. This procedure ensures that the LUT is properly updated. If possible, use a stable light source to ensure that fluctuations in subsequent acquisitions do not prevent proper optimization of the different parameters.

A recommended alternative is to capture a suitable image for the optimization process (or load a previously saved image), and then enable the “**Use Current Image**” slider in the Spectrum Window. The unwrap parameters can then be optimized on this one image. Don’t forget to hit “**calculate stripe overlay**” before unwrapping again after any change to the unwrap parameters.

7.2.2 Optimize the Display increments parameter

This parameter serves two functions. First, it determines the wavelength increment used in the spectrum display. Second, it determines the wavelength separation of successive points when saving a spectrum to a CSV file. **It is recommended that the minimum value of this parameter be set to 0.2 of the instrument resolution.** Using a smaller value does not provide any additional information in the spectrum, and often results in very large CSV files. It is sometimes useful to set the “Display increments” value to several times the instrument resolution to obtain more manageable file sizes, particularly when there are no narrow features of interest in the spectrum. **Be sure to hit “calculate stripe overlay” after each change of the “Display increments” parameter** (this ensures the LUT is properly updated), and then acquire a new spectrum to assess the change.

If your spectrometer shipped with an external etalon module, and you use the “**Mapping Calibration**” method of calibration described in Section 6.4, you must carry out a full “**Mapping Calibration**” whenever the “**Display Increments**” parameter is changed.

7.2.3 Optimize the Gaussian Smoothing Parameter

Once the “bin” width for collecting and averaging the (λ , I) pairs along the wavelength axis has been set by the Display increments parameter, it is usually beneficial to carry out a further sliding average over several bin widths. The Gaussian Smoothing parameter in SpectraLoK

sets the width of this sliding window and then applies a Gaussian averaging method. If the parameter is set to 11, the sliding average includes the central wavelength bin (with a width of 1 pm, for example), plus 5 bins to the longer and shorter wavelength. (For this reason, the Gaussian Smoothing parameter will default to an odd number whenever an even number is entered). The resulting sliding average will have an effective width of ~5 pm when the bins are 1 pm wide.

*A significant improvement in Signal-to-Noise ratio can be obtained for all displayed spectra by increasing the value of the Gaussian Smoothing parameter until the widths of any sharp spectral features begin to broaden. It is worth experimenting with both the “Display increments” parameter and the “Gaussian Smoothing” parameter to optimize the displayed spectrum. **Be sure to hit “calculate stripe overlay” after each change of parameter**, and then acquire a new spectrum to assess the change.*

Note that both the “Display increments” and “Gaussian Smoothing” values are optimized in the original Configuration file to unwrap narrow spectral features that require the maximum instrument resolution.

7.2.4 Optimize the Region of Interest (ROI) for the unwrapping

The Settings Window provides four parameters that can be used to limit the region of the sensor that is examined in the unwrapping process. These four parameters, “Left, Right, Upper and Lower unwrap limits” are set in the original Configuration file to provide the **recommended maximum unwrap area** on the sensor (for many spectrometers this area will include the entire sensor area; for other spectrometers regions outside the recommended area contain very little light or are subject to significant aberrations that prevent accurate unwrapping).

The values of the Left and Right limits can be changed to unwrap a smaller area if you want to limit the range of wavelengths unwrapped (and also increase the unwrapping speed). For example, in Brillouin spectroscopy, only a small range of wavelengths near the pump laser is of interest. The “Left and Right unwrap limits” can be set to display only the wavelength region of interest. Experiment with the value of these two parameters to optimize the unwrapping speed without compromising the wavelength region of interest.

In a similar fashion, the “Upper unwrap limit” and “Lower unwrap limit” parameters can be set to limit the vertical extent of the sensor area that is unwrapped. (Note that the top of the sensor has **smaller** pixel values than the bottom of the sensor – this is the convention used by camera sensor displays). In general, limiting the vertical extent of the unwrapping may slightly reduce the SNR in the spectrum (as fewer orders (FSRs) are unwrapped), but can increase the unwrapping speed. *The selected ROI can be observed in the Camera View by clicking on “Overlays” followed by “Unwrap Area”.*

Do not go outside the boundaries of the maximum unwrap area as defined in your original Configuration file. ***Be sure to hit “calculate stripe overlay” after each change of ROI parameter**, and then acquire a new spectrum to assess the change.* The original Configuration

File shipped with your spectrometer defines the maximum useful ROI (or unwrap area). If you increase your ROI beyond these factory settings, an error message will result when you attempt an unwrap.

7.2.5 Optimize the Gaussian Stripe Width Unwrapping Parameter

Once a spectrum is displayed in the Spectrum window, it is worth varying the value of the Gaussian Stripe Width in the Settings window to optimize the display and Signal-to-Noise ratio. *Before experimenting with the parameter value, make sure that the stripe overlay is almost centered on the spectral features of interest. Complete a **Quick Calibration** if it is not centered.* Now, set the Gaussian Stripe Width to “None”. With this setting, the software only considers the single pixel at the centre of the stripe during the unwrapping process. Next increase the value of the Gaussian Stripe Width to Gaussian3, Gaussian5, and finally Gaussian7. **Be sure to hit “calculate stripe overlay” after each change, and then acquire a new spectrum to assess the change.** For each value observe the unwrapped spectrum. While the displayed value of Intensity tends to decrease as the Gaussian Stripe Width increases and includes less intense neighbouring X-pixels, the Signal-to-Noise ratio improves, as the effect of pixilation is reduced. The value of the Gaussian Stripe Width should only be increased until the magnitude of any FSR crosstalk becomes a problem. The value of the Gaussian Stripe Width parameter should usually be set to the approximate width of the stripes (in pixels). Note that the original Configuration file contains the optimum value of the Gaussian Stripe Width, as determined at LightMachinery.

If you choose to use a value of the Gaussian Stripe Width that **differs** from the one in your original Configuration file, it is recommended that you complete a new **Grating Calibration** (including the “**calculate ICE and correct stripes**” step) as described in Section 6.1.3. This ensures that the ICE correction parameters are updated to reflect the new value of the Gaussian Stripe Width. If you are using an external etalon for calibration, please carry out a new **Mapping Calibration** to update the ICE correction parameters.

7.2.6 Enable ICE Correction.

It is usually better to check the **Enable ICE** box in the Settings Window.. This will ensure a better calibration of the intensity axis in the Spectrum Window.

Once a spectrum is displayed in the Spectrum Window, it is worth comparing the spectrum with the “Enable ICE Correction” box checked and unchecked in the Settings Window. Remember to **calculate stripe overlay** every time a change is made. Typically, the box is best left checked, especially when examining signals from broadband sources.

NOTICE

When **Enable ICE** is checked, it is highly recommended to systematically subtract a background (see section 7.2.9) when performing measurements.

Otherwise, the background noise (dark current) will appear modulated rather than flat.

7.2.7 Enable Vertical Envelope Correction

Once a spectrum is displayed in the Spectrum Window, it is worth comparing the spectrum with the “Enable Vertical Envelope Correction” box checked and unchecked in the Settings Window. Remember to “calculate stripe overlay” every time a change is made. Typically, the box is best left checked, especially when examining signals from broadband sources.

NOTICE

When Vertical Envelope Correction is enabled, it is highly recommended to systematically subtract a background (see section 7.2.9) when performing measurements. Otherwise, the background noise (dark current) will appear modulated rather than flat.

7.2.8 Averaging a Series of Spectra

When studying weak spectral features, it is often beneficial to take an average of successive captured spectra. Averaging several images often increases the Signal-to-Noise ratio of the displayed spectrum.

To enable the spectrum averaging function:

1. Connect the light source you want to measure and select the appropriate gain and exposure (make sure you are below saturation).
2. Under SPECTRUM CONTROL, enable the **Enable Averaging** slider.
3. Set the **Number of Spectra to be Averaged** to the desired number (e.g. 5).
4. Click on “single” if you wish to stop after a single average. Otherwise, click on “capture” and the software will display successive averaged spectra (updating after the product of the exposure time multiplied by the value set in Average Control).
5. The Status bar will indicate if the camera is capturing images (capturing) or not (open).

7.2.9 Background Subtraction

Subtracting a background (or dark) spectrum is often required when looking at weak signals, or to eliminate the effects of bright or “hot” pixels.

NOTICE

In certain models, subtracting a background is **required** to prevent background-related intensity modulation artifacts. For all spectrometers, it is

always preferable to perform background subtracting (typically with averaging, see next subsection) prior to performing a measurement.

To enable background subtraction:

1. Connect the light source you want to measure and select the appropriate gain and exposure (make sure you are below saturation).
2. Turn off the light source to acquire the background spectra.
3. Under SPECTRUM CONTROL, click **clear background** and then click **capture background**.
4. Turn on the light source, and then click **unwrap** to display a spectrum with the background subtracted.
5. Click **clear background** to return to the normal display without background subtraction.

ATTENTION!

Steps 2-4 **must** be repeated whenever the gain or exposure settings of the light source are changed.

Alternatively, you can use the button **use Current Image as Background** in the Camera Window. This allows users the ability to load in previously saved images (or to import previously exported images) and utilize them for background subtraction.

Note that a background acquired or applied in the Camera Window is simultaneously applied in the Spectrum Window.

Whenever Background Subtraction is enabled, a small icon, , will appear in both the Camera Window and the Spectrum Window. This icon will disappear upon clicking the Clear Background button.

7.2.10 Background Subtraction with Averaging.

To improve the signal-to-noise obtained with weak light sources, perform a background subtraction in conjunction with averaging.

To enable background subtraction with averaging:

1. Connect the light source you want to measure and select the appropriate gain and exposure (make sure you are below saturation).
2. Turn off the light source to acquire the blank spectra.
3. Under SPECTRUM CONTROL, click **clear background**.
4. Under SPECTRUM CONTROL, enable the **Enable Averaging** slider.
5. Set the **Number of Spectra to be Averaged** to the desired number (e.g. 5), and then click **capture background**.
6. Turn on the light source and click “single” if you wish to stop after a single average with background subtraction. Otherwise, click on “unwrap” and the software will display successive averaged spectra (updating after the product of the exposure time multiplied by the value set in Average Control).

7. The Status bar will indicate if the camera is capturing images (capturing) or not (open).

NOTICE

The Spectrum Window will now display the difference between 5 (for example) samples acquired with the light source and 5 samples acquired with only the “dark” background. In response to any changes in the light source, the spectrometer display will change only on a timescale of ~5 times the exposure.

7.3 Saving Spectra

SpectraLoK can save spectra as a .csv file, which can then be imported to a spreadsheet for further analysis. The steps for saving spectra are discussed below (see Section 4 - Spectrometer software for descriptions of the functions used).

7.3.1 Saving a single spectrum

The spectrum currently being displayed can be saved in the following way:

1. Follow the steps outlined in **Section 7.1** to acquire a single spectrum. This is the spectrum that will be saved.
2. Ensure that the acquisition (unwrap) is stopped.
3. Click “**save to csv**” to select a desired save location.
4. Click “**save**”. This will save the current displayed spectrum to the selected location.
5. Optional - To save a custom CSV wavelength range:
 - a. Enable the “save custom CSV range” slider.
 - b. Choose the range to be saved by zooming into the area of interest in the chart or by typing the values into the boxes.
 - c. Click “**save to csv**”. This will save the current displayed spectrum to the selected location based on the values in the X Min and X Max boxes

7.3.2 Saving multiple spectra as they are displayed in real time

Multiple spectra can be saved by clicking **Enable burst spectra storage**. This can be used in combination with **Enable Averaging**. Since the spectra being saved are those being displayed in real time, the acquisition (and thus saving) rate will often be limited by the unwrapping time, as opposed to being limited by the maximum frame rate of the camera or the exposure time. To prevent this, use the fast capture methods discussed in the subsequent sections (7.3.3 and 7.3.4).

To save multiple spectra:

1. Follow the steps outlined in **Section 7.1 - Acquiring a spectrum** in order to optimize the exposure and other parameters to be used for the spectra that you will save.
2. Click **Enable burst spectra storage**.
3. Specify the number of images to burst (i.e. the number of images that you want to save).

4. Click “**save to csv**”. Please note that you must have previously captured at least one spectrum via the unwrap button or the single button for the “save to csv” button to be enabled.
5. Choose the file location and name for the .csv files, click “**save**”, the capture will start immediately
6. Optional - To save a custom CSV wavelength range:
 - a. Complete step 1.
 - b. Enable the “save custom CSV range” slider.
 - c. Choose the range to be saved by zooming into the area of interest or by typing the values into the boxes. Note that this is the range that will be used for all of the acquired spectra throughout the burst spectra process and that any alterations made to the range while the burst process is running will not alter the range saved.
 - d. Complete steps 2-5.

7.3.3 Fast Capture Multiple Spectra (burst number < 100)

Fast capture mode may be beneficial to users who need to acquire multiple spectra at speeds limited by the maximum frame rate of the camera or the exposure time.

CAUTION

With burst numbers greater than 100 or low system memory, **Enabling post capture unwrap** can cause instability and crash SpectraLoK.

To save multiple spectra using fast capture mode for a burst number less than 100:

1. Follow the steps outlined in **Section 7.1 - Acquiring a spectrum** in order to optimize the exposure and other parameters to be used for the spectra that you will save.
2. Click **Enable burst spectra storage**.
3. Specify the number of images to burst (i.e. the number of images that you want to save).
4. Click **Enable post capture unwrap**.
5. Click “**save to csv**”. Please note that you must have previously captured at least one spectrum via the unwrap button or the single button for the Save to CSV button to be enabled.
6. Choose the file location and name for the .csv files, click “**save**”, the capture will start immediately
7. Optional - To save a custom CSV wavelength range:
 - a. Complete step 1.
 - b. Enable the “save custom CSV range” slider.
 - c. Choose the range to be saved by zooming into the area of interest or by typing the values into the boxes. Note that this is the range that will be used for all of the acquired spectra throughout the burst spectra process and that any alterations made to the range while the burst process is running will not alter the range saved.

- d. Complete steps 2-6.

Note that after the acquisition of the specified number of frames, SpectraLoK must finish processing each image before continuing.

7.3.4 Fast Capture Multiple Spectra (burst number > 100)

When fast capture mode is required for burst numbers larger than 100, the **Enable hard drive buffering** function can greatly improve stability.

ATTENTION!

Enable hard drive buffering will significantly increase the processing time for each spectrum to be saved.

To save multiple spectra using fast capture mode for burst numbers greater than 100:

1. Follow the steps outlined in **Section 7.1 - Acquiring a spectrum** in order to optimize the exposure and other parameters to be used for the spectra that you will save.
2. Click **Enable burst spectra storage**.
3. Specify the number of images to burst (i.e. the number of images that you want to save).
4. Click **Enable post capture unwrap** and **Enable hard drive buffering**.
5. Click “**save to csv**”. Please note that you must have previously captured at least one spectrum via the unwrap button or the single button for the Save to CSV button to be enabled.
6. Choose the file location and name for the .csv files, click “**save**”, the capture will start immediately
7. Optional - To save a custom CSV wavelength range:
 - a. Complete step 1.
 - b. Enable the “**save custom CSV range**” slider.
 - c. Choose the range to be saved by zooming into the area of interest or by typing the values into the boxes. Note that this is the range that will be used for all of the acquired spectra throughout the burst spectra process and that any alterations made to the range while the burst process is running will not alter the range saved.
- d. Complete steps 2-6.

Note that after the acquisition of the specified number of frames, SpectraLoK must finish processing each image before continuing.

7.3.5 Saving Multiple Spectra with Timed Spectra Storage

Multiple spectra can be saved every X seconds for the next Y seconds by clicking **Enable timed spectra storage**. This can be used in combination with **Enable Averaging**. Since the spectra being saved are those being displayed in real time, the acquisition (and thus saving)

rate will often be limited by the unwrapping time, as opposed to being limited by the maximum frame rate of the camera or the exposure time.

To save multiple spectra:

1. Follow the steps outlined in **Section 7.1 - Acquiring a spectrum** in order to optimize the exposure and other parameters to be used for the spectra that you will save.
2. Click **Timed burst spectra storage**.
3. Set desired Time between spectra (s) (eg. 5 seconds).
4. Set desired length of time to capture spectra (s) (e.g. 30 seconds).
5. Specify the number of images to burst (i.e. the number of images that you want to save).
6. Click “**save to csv**”. Please note that you must have previously captured at least one spectrum via the unwrap button or the single button for the Save to CSV button to be enabled.
7. Choose the file location and name for the .csv files, click “**save**”, the capture will start immediately
8. Optional - To save a custom CSV wavelength range:
 - a. Complete step 1.
 - b. Enable the “save custom CSV range” slider.
 - c. Choose the range to be saved by zooming into the area of interest or by typing the values into the boxes. Note that this is the range that will be used for all of the acquired spectra throughout the burst spectra process and that any alterations made to the range while the burst process is running will not alter the range saved.
 - d. Complete steps 2-8.

7.4 Real-Time Analysis Using Chart Control Features

Various features are included in SpectraLoK to perform analysis in real-time, including: displaying cursors and determining the distance between them; finding the peak within a given range; determining the FWHM of a feature; switching to a relative scale; etc. They are discussed below (descriptions are also included in Section 4 - Spectrometer Software).

7.4.1 Cursors

Cursors are lines that may be shown in the Spectrum Window as a way for the user to interact with the data on screen.

Display Cursors

1. Open the **Spectrum** menu at the top of the screen.
2. Click **Hide Min / Center / Reference / Max** to uncheck the item and display the cursors. If the cursors cannot be seen, type F to display them in the current Spectrum Window.
3. Once finished, click **Hide Min / Center / Reference / Max** to hide the cursors.

Reset Cursors

1. Open the **Spectrum** menu at the top of the screen.
2. Click **Reset Min / Center / Reference / Max**
3. Alternatively, press '**F**' on your keyboard

Determine the distance between the cursors

1. The distances between the cursors are displayed in the top right corner of the Spectrum Window.

Find the peak within a given range

1. Bracket the peak with the Min and Max cursors by clicking on and dragging the Min and Max cursors to appropriate locations.
2. Under CHART CONTROL on the right side of the window select **find highest peak** or **find lowest trough** depending on your requirements.
3. The Reference cursor will be placed at the highest (or lowest) measured intensity point within the range of the Min and Max cursors.

Determine the FWHM of a feature

1. Bracket the peak with the Min and Max cursors by clicking on and dragging the Min and Max cursors to appropriate locations.
2. Under CHART CONTROL on the right side of the window select **find highest peak** or **find lowest trough**.
3. Select **find fwhm of peak** or **Find fwhm of trough**
*Note that **find fwhm of trough** is not yet implemented, but is planned for a future release.*
4. Cyan reference lines will be placed at the half max of the peak on either side.
5. A dialog box will appear at the peak showing the FWHM of the peak. A center line will also be placed at the highest point within the FWHM. This line cannot be modified directly by the user.

Clear Center Cursors

1. Open the **Spectrum** menu at the top of the screen.
2. Click **Reset Clear Center Cursors**.

7.4.2 Scale

The scale of the chart may be modified to best suit your needs.

Switch to a relative scale

1. Move the Reference cursor to the location you wish to act as the zero in the wavelength axis. The Reference location can also be set using **find highest peak** or **find lowest trough**.
2. Under CHART CONTROL on the right side of the screen window **set reference to zero**.

Switch to absolute scale

Under CHART CONTROL on the right side of the window select **reset axis**.

Change Y axis units to log10

1. Open the **Axis Control** menu at the top of the screen.
2. Click on **Axis Control**.
3. Click on **Y Axis (Intensity)**.
4. Click **Use Log10 Axis**.

Change X axis units

1. Open the **Spectrum** menu at the top of the screen.
2. Click on **Controls**.
3. Click on the dropdown box to the right and select the preferred units.

NOTICE

When converting the X-axis units to any absolute frequency measurements (**Spectrum>Controls>Measurement>****KHz/MHz/GHz/THz*****), SpectraloK assumes that the wavelengths are measured in vacuum. If using reference wavelengths in air, the user must take into account the refractive index of air (~1.00028) when converting to frequency measurements.

7.4.3 Overlaying Spectra

The Spectrum Window can display multiple data sets for comparison;

- **Current (Green):** The most recent spectrum unwrap.
- **Reference (Red):** The most recently saved data for comparison.
- **File (Blue):** The imported data from a previous unwrap. (Not modifiable)

The Current data set is the data from the most recent unwrap. If you would like to keep this data for comparison it may be kept as a reference. To do this, select Data at the top of the window and click on Keep Current Unwrap. Upon the next unwrap the current data will be shifted into the reference data set.

The File data set allows you to view unwrap data that was saved into a csv file. To view previously saved data, select Data then Open File and select the csv file you wish to view. The loaded data may not be modified in the same way as Current/reference as the Chart Controls will not be functional for the loaded data.

7.4.4 Display Spectrum Ratio

The Spectrum Window can display the ratio between a current spectrum unwrap and a reference spectrum unwrap for comparison. This feature is particularly useful for transmission measurements, for instance.

To display spectrum ratios in the Spectrum Window:

1. Acquire a reference spectrum.
2. Open the Data menu at the top of the screen and click Keep Current Unwrap.
3. Acquire a new spectrum. The reference spectrum will be retained and displayed in red.
4. Open the Data menu at the top of the screen and click Display Ratio. The current unwrap (displayed in green) will now be displayed as a ratio of the two unwraps.
5. The spectrum displayed as a ratio can be reverted by simply clicking Display Ratio again.

To clear the reference unwrap, open the Spectrum menu at the top of the screen and click Clear Reference.

7.4.5 Labelling peaks in a Spectrum

A label can be added to any peak in the Spectrum Window by right-clicking anywhere in the Window, and then editing the text in the label box that appears. If you wish the label box to snap to the position of the intensity peak, go to the dropdown menu under Spectrum, and click on **Enable snapping of label to peak**. The label box can be deleted by clicking on the “X” near the box.

7.5 Grating rotation

Rotating the angle of the grating within your spectrometer allows the wavelength range falling upon the sensor to be changed. In other words, changing the angle of the grating increases or decreases the central wavelength on the sensor.

ATTENTION!

*Remember to always perform a **Full Calibration** after adjusting the grating angle.*

7.5.1 Grating Rotation (units with a motorized grating)

The grating can be rotated by using the controls in the Grating Rotation Stage window. In this window, you can enter the desired wavelength in nanometers or the angular position of the rotation stage in degrees. Clicking “go!” will first rotate the grating to Home and then rotate to the specified position placing that wavelength/angle in the exact center of the sensor. The motorized stage first rotates to Home before moving to the desired position to minimize any backlash errors. The progress of the motorized grating can also be observed in the status bar at the bottom of the page during the motion.



Figure 7-3 Grating Rotation Stage window.

The dropdown menu accessed by clicking the “Grating Rotation Stage” header provides three additional functions described below:

- Save current position: This saves the current position of the axis
- Go to saved position: This will rotate the grating to Home and then to its saved position
- Home: This will home the axis. Upon homing, the axis moves towards one end of its travel range until it reaches the fixed reference point known as Home.

For a large change in the value of the central wavelength (>25 nm), it is often preferable to remove the top cover and to also optimize the focus of the imaging lens. Remember that this focus is changed by translating the imaging lens stage, not rotating the focus ring. If the grating rotation was small (i.e. corresponding to less than ~25nm), you can proceed directly with the Full Calibration. However, for larger grating rotations, or if you want to ensure optimized performance, it is recommended to remove the top cover, put powder-free gloves on, and adjust the imaging lens focus before carrying out a Full Calibration.

7.5.2 Grating Rotation (units **without** a motorized grating)

The rotational mount of the grating is accessible from outside the unit (Figure 7-3), and this access can be used for small changes in grating angle (resulting in a wavelength change of < 25 nm). However, for a large change in grating angle, it is often preferable to remove the top cover and to also optimize the focus of the imaging lens. Remember that this focus is changed by translating the imaging lens stage, not rotating the focus ring.

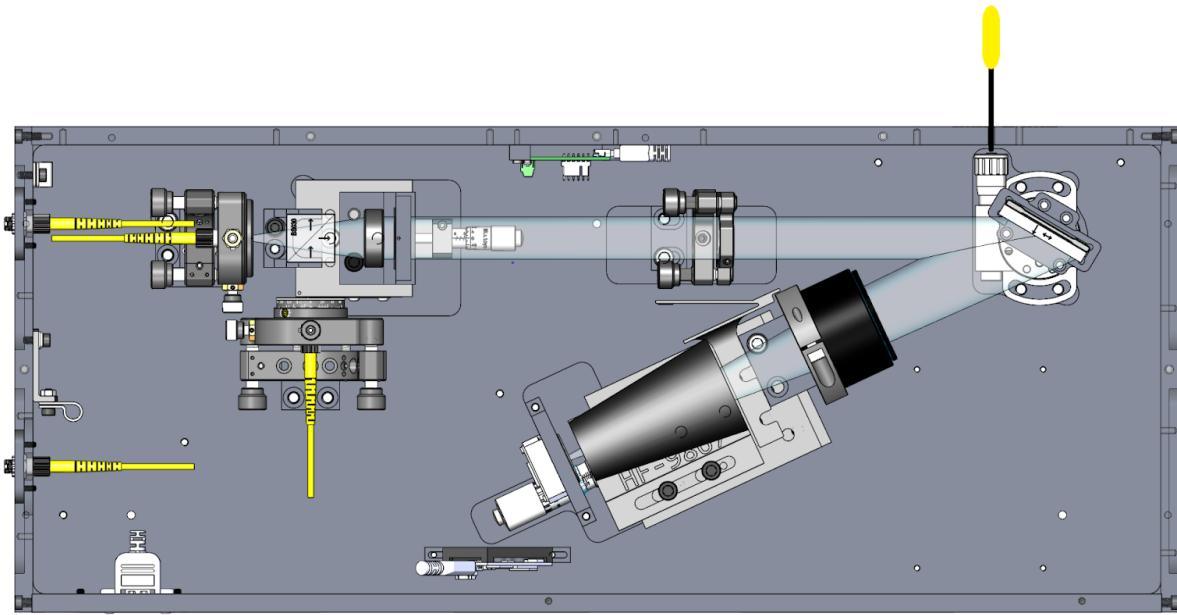


Figure 7-4 The external access point for a grating rotation is indicated for a LightMachinery spectrometer (insert the supplied ball-end driver as represented by the schematic yellow and black tool).

There are three different methods for performing a grating rotation.

7.5.2.1 Grating Rotation Method 1 (recommended for accurate wavelength setting without removing the spectrometer lid)

This method is ideal when the required spectral range is known. The following procedure gives the instructions for determining the grating position for a specific wavelength.

Procedure:

1. Connect a broadband source and obtain an image of the stripes at the current grating position, as described in the Section 6.1.3 Grating Calibration. Carry out steps 1-6 of the Grating Calibration to ensure you have a good image of the stripes at the current grating position.
2. In the Camera View, first click on the **Overlays** tab and then check the **Calibration Peak**. This will display a small arrow at the reference position on the sensor (the X-position corresponds to the position of the Etalon Calibration blobs in the saved configuration). Next click on the **Wavelength** tab, and then click on **Estimate from broadband signal**. The software will carry out a Grating Calibration, and will vary *the wavelength at the reference position* to determine the best fit to the experimental stripe positions. The calibration procedure takes some time (including capturing a new image of the stripes), and progress can be followed in the messages at the bottom of the Camera View. Once the calibration is complete, the software reports

- the results, including the wavelength at the Calibration Peak. This wavelength should be very close to the value used in the saved Etalon Calibration.
3. Next, rotate the grating using the ball-end driver as indicated in Fig 7-3. A rotation in the clockwise direction generally *decreases* the wavelength on the sensor. It is suggested that approximately one-tenth of a complete rotation (~30 degree rotation) of the ball-end driver be initially attempted in the required direction. Record another image of the stripes, adjusting the exposure, Gain, and background subtraction if required. Once a good set of stripes have been obtained, click Stop to freeze the image. Then, in the Camera View, click on the **Wavelength** tab, and then click on **Estimate from broadband signal**. Once again, the software will capture a new image, carry out a Grating Calibration, report the new “best fit” wavelength for the experimental stripes, and snap the predicted stripes positions (if displayed) to the new stripe positions.
 4. The process described above can be repeated several times to give incremental changes in the wavelength range on the sensor, until the required grating position is found. Alternatively, the change in wavelength for one-tenth of a turn of the driver can be compared with the required change in wavelength and an estimate made of the remaining rotation of the driver required. Either way, clicking on **Estimate from broadband signal** will return the wavelength of the current stripe image. Once the wavelength (at the position of the Calibration Peak) is correct, the stripes should be inspected across the ROI to ensure the focus is still good. If the grating rotation was small (i.e. corresponding to less than ~25nm), you can proceed directly with the **Full Calibration**. However, for larger grating rotations, or if you want to ensure optimized performance, it is recommended to remove the top cover, put powder-free gloves on, and adjust the imaging lens focus before carrying out a **Full Calibration**. Refer to the next section (Section 8 – Maintenance) of this manual for more information on imaging lens focus adjustments.
 5. Optional – to avoid capturing a new image after clicking on Estimate from broadband signal in the Camera View, first launch the Grating Calibration window, and enable “use current image” before returning to the Camera View and clicking on Estimate from broadband signal. The software will carry out a calibration using the current image, report the new “best fit” wavelength for the experimental stripes, and snap the predicted stripes positions (if displayed) to the new stripe positions.

7.5.2.2 Grating Rotation Method 2 (requires removing the spectrometer lid)

This method can be used when the required spectral range is known. The following procedure gives the instructions for determining the grating setting for a specific wavelength, and how to rotate the grating to the new setting.

Procedure:

1. Determining the correct grating angle and rotating the grating.
 - a. Remove the top cover of the spectrometer, and note the position of the grating rotation stage as shown in Figure 7-4.



Figure 7-5 Grating rotation stage set to 120 degrees). Your grating stage may have an arrow sticker pointing towards the scale; in that case use the arrow as opposed to etched scale.

- b. Each spectrometer is calibrated at LightMachinery, and the relevant grating calibration factors are included in the Test Report shipped with each spectrometer (please contact LightMachinery if this information is missing). Four parameters are required – the grating line density in lines/mm, the zero order angle in degrees, the first order angle in degrees, and the calibration wavelength in nm. Note the values of these parameters for your spectrometer.
 - c. Go to the link below (see Figure 7-5):
<https://lightmachinery.com/optical-design-center/more-optical-design-tools/spc/>
Enter the four parameters into the first four Grating Parameter boxes on the left side of the web page. In the final box on the left side, *enter the wavelength that is desired to fall on the center of the sensor after a grating rotation*. In the Spectrometer Performance section of the website note the angle shown below the Grating Setting heading. (The website also shows a graph of wavelength versus grating angle as shown in Figure 7-5). Full details are provided under “User’s Guide” at the top of the web page.
2. Now carefully rotate the grating stage until it is set to the angle indicated below the Grating Setting heading, using the rotation knob indicated in Figure 7-4. This should result in the desired wavelength being close to the center of the sensor.

3. Finally, replace the spectrometer cover and connect the light source appropriate to the new wavelength range.
4. Open SpectraLoK, select the proper camera and configuration file, and open the Camera Window.
5. Examine the image of the light source in the Camera Window. If required, make minor adjustments to the grating angle to place spectral features in the desired part of the sensor, using the ball-end driver inserted into the Grating Rotation access hole (see Figure 7-3). If this particular wavelength range is to be selected on a regular basis, it is worth removing the top cover and recording the exact position of the grating rotation stage for future use.
6. If the grating rotation was small (i.e. corresponding to less than ~25nm), you can proceed directly with the **Full Calibration, including an Intensity Axis Calibration if “Enable Intensity Axis Correction” is checked in the Settings Window** (typically for an experiment that requires very accurate **relative** intensities over a wide wavelength range). However, for larger grating rotations, or if you want to ensure optimized performance, it is recommended to remove the top cover, put gloves on, and adjust the imaging lens focus. Refer to the next section (Section 8 – Maintenance) of this manual for more information on imaging lens focus adjustments.

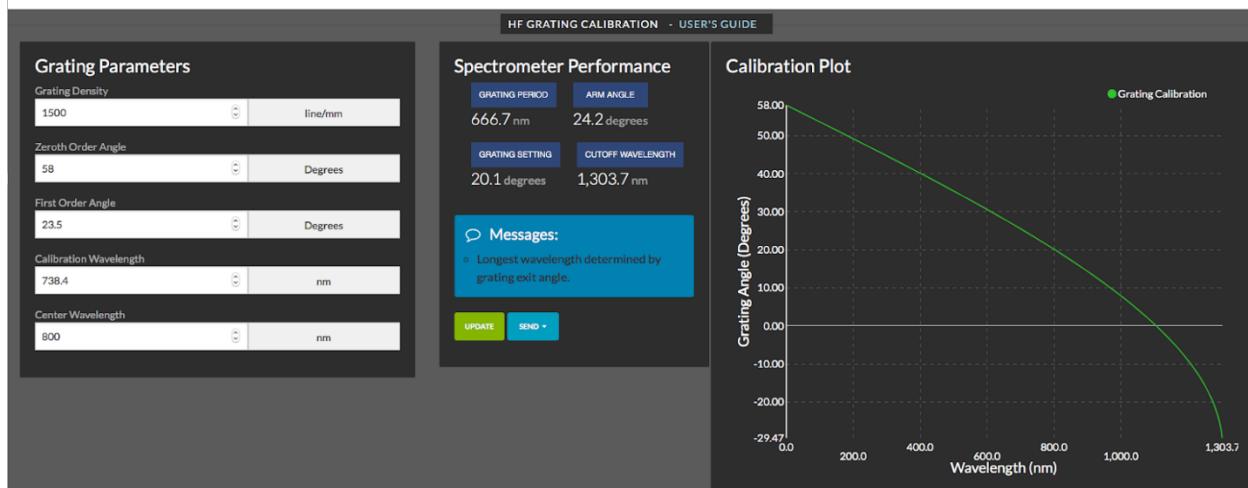


Figure 7-6 Typical web page from LightMachinery calculator for grating calibration.

7.5.2.3 Grating Rotation Method 3

This method may be required when the light source under study is not well known, i.e., when the required spectral range is not well known a priori.

Procedure:

1. Open SpectraLoK, select the proper camera , select the proper configuration file, and open the Camera Window.
2. Set the exposure to ~200 ms, and the camera gain to maximum. Increase Software Gain to ~10 and capture a background (with no light source).
3. Connect the source that you wish to analyze to the spectrometer. Ideally, the power should initially be somewhere between 100 pW and 0.1 mW for single wavelength

sources, and significantly higher for broadband sources (lower powers can be used during actual measurements once the grating rotation is completed). The next step is designed to ensure that the wavelength of this source falls on the camera sensor.

4. Click capture, and slowly rotate the grating stage until you see a series of blobs, stripe sections, or full stripes move across the screen (in the case of laser sources, in particular, the series of blobs will generally be highly saturated). Continue rotating the grating stage until the features are roughly in the center of the screen. As the range of wavelengths displayed on the sensor at any given grating position is limited, *it is important to ensure that the signal is not missed due to overly rapid tuning of the grating.*
5. If the grating rotation was small (i.e. corresponding to less than ~25nm), you can proceed directly with the **Full Calibration**. However, for larger grating rotations, or if you want to ensure optimized performance, it is recommended to remove the top cover, put gloves on, and adjust the imaging lens focus. Refer to the next section (Section 8 – Maintenance) of this manual for more information on imaging lens focus adjustments.

7.6 External Triggering (certain models only)

Certain spectrometer models support external hardware triggering. For such models where the camera is internal, a BNC or SMA connector is made accessible to the user. For models where the camera is external, the original camera trigger connector is directly exposed to the user. For the IRIS camera, this is a MMCX cable.

External trigger requirements:

- For spectrometer models where the camera is external, please refer directly to the camera manufacturer's documentation;
- For spectrometer models where the camera is a Pixelink model, your external trigger signal must meet the following requirements (see Figure 7-6):
- T_{high} is greater than 10 μ s and less than or equal to the exposure time.
- Ensure the trigger repetition rate is less than or equal to maximum camera capture rate (with a low duty cycle).
- The triggering voltage (T_{high}) is between 3.3 and 5V (a hybrid of TTL and CMOS).
- Exposure starts on the rising edge of the trigger pulse.
- Refer to the camera manufacturer website for further details.
- For spectrometer models where the camera is an IRIS model, the sensor is CMOS and thus should be triggered between 3.5V and 5V. The start of acquisitions begins on the rising edge for this camera as well.

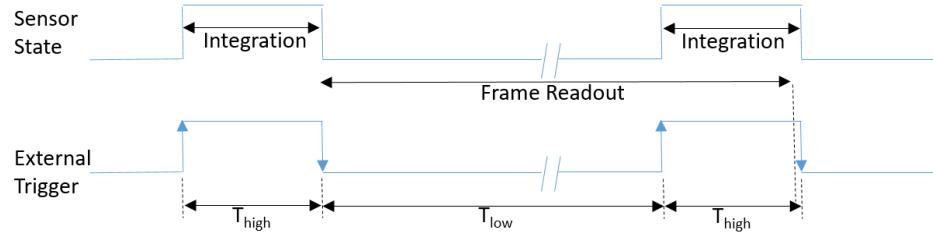


Figure 7-7 External signal pulse example.

Procedure to connect an external trigger source to the LightMachinery spectrometer and enable external triggering:

1. In the Settings window, set the camera trigger type to external.
2. Connect your external trigger signal source to the appropriate spectrometer (or camera) connector.

NOTICE

Make sure your signal meets the signal requirements listed above.

3. In the Camera or Spectrum window, click the Capture, Unwrap, Single, or Save to CSV button; acquisition will take place only when an external trigger signal is sent.

Section 8 - Maintenance

The maintenance required depends on the usage (in particular whether the grating is frequently rotated or not in applicable models), and mechanical disturbances (e.g. moving the spectrometer to a new lab). Aside from the procedures described in the operation section (section 7), various procedures described in the context of the installation (section 5) may be required on occasion. This is summarized below.

Performing the alignment check described in section 5.3 at regular intervals is recommended to ensure the light source is optimally coupled into the spectrometer. If in doubt, repeat the complete installation procedures or contact us for assistance.

In all cases it is required, but not necessarily sufficient, to confirm that:

1. A broadband source produces on the camera a signal consisting of distinct stripes similar to those shown in Figure 5-3;
 2. A narrow-band source produces on the camera a signal consisting of distinct blobs similar to the one shown in Figure 5-4;
 3. The narrow-band blobs from the SMF input fall on the broadband stripes from the MMF input
 4. The calibration reflects the current alignment and can successfully overlay experimental stripes (as shown in figure 6.3) over the region of interest given that a recent **Quick Calibration** was performed.
-
- Perform a **Full Calibration** or **Mapping Calibration** procedure whenever alignment changes have occurred in the instrument, or the grating has been rotated – see Section 6.1;
 - Recall the spectrometer has two inputs combined into a single path by a cube beam combiner. For the calibration procedure to be successful, the two inputs must be at equivalent positions horizontally with respect to the collimating lens; if the blob does not land on the stripe, adjust the horizontal position of the tip of the MMF fiber. Use a narrow band source, swapping between the inputs until the position is overlapped, in particular before you perform a Full calibration – see Section 5.3.2;
 - Adjust the vertical position of the tip of the SMF fiber only if the signal intensity is lower than expected or if the vertical intensity profile is far from being roughly centered onto the sensor – see Section 5.3.2;
 - Adjust the imaging lens focus only if the grating angle is changed significantly (resulting in a change in the wavelengths incident on the camera of more than 20nm), or if there is a significant amount of crosstalk observed in the unwrapped spectrum – see Section 5.3, Figure 5-10;

Section 9 - Troubleshooting

This Troubleshooting Section contains solutions to possible issues that may occur during the installation and operation of the spectrometer. If you are experiencing issues with the installation of the SpectraLoK software, refer to Troubleshooting at the end of Section 3. If you are experiencing issues with the calibration procedures, refer to Troubleshooting at the end of Section 6.

NOTICE

Contact LightMachinery using the information at the beginning of this manual if you encounter any persistent problems.

9.1 Logging of Warnings and Errors

SpectraLoK uses the following library to track warnings and errors:

<https://nlog-project.org/>

SpectraLoK is configured by default to log warnings and errors under the logs directory where it is installed (usually: C:\Program Files\LightMachinery\SpectraLoK_x64).

The log directory contains one file for warnings (warnings.log) and another file for errors (errors.log); these files are archived every day for the previous seven days.

If the computer is connected to the Internet, SpectraLoK will attempt to log the warnings and errors in a secure cloud environment. Errors and warnings are reviewed by our development team to help fix potential problems that may arise. If you want to disable this online logging feature, edit the “SpectraLoK.exe.config” with a text editing application (Microsoft Notepad, for example) and delete the following line:

‘<logger name=”*” minlevel=”Warn” writeTo=”aws”/>’

NOTICE

The next three sections deal with the problems of noisy signals, FSR crosstalk in the measured spectrum, and weak signals. If you suffer from any of these problems, first check that all optical fiber cables (SMF or MMF) are properly seated in the mating connectors. Pay particular attention to any connection that has been modified since the signal behaved as expected. Incorrect fiber cable connection is a common cause of problems with the optical signal.

9.2 Signal Stability Worse Than Expected

If the observed spectrum contains more noise than expected, verify that the noise is not originating from the source itself, or from the coupling between the source and input port, before performing these troubleshooting steps:

1. Minimize gain: lower the gain to the minimal value and increase the exposure until near-saturation is achieved.
2. Maximize exposure: aim for an exposure > 100ms since this provides a more stable signal. If the exposure required to prevent saturation at minimum gain is < 100ms, lower the intensity of the signal being characterized using filters (for example).
3. Fiber type: Use an SMF fiber optic cable when measuring a laser source. An MMF fiber optic cable will produce a speckle pattern, increasing the amount of signal noise.
4. Vibrations: ensure that the spectrometer is placed on a stable table that is free of vibrations.
5. Fiber connections: check that the fiber optic cable types match (SMF connected to SMF, FC/PC to FC/PC). If the source output is APC, use an APC-to-PC hybrid patch cable.
6. Perform a **Quick Calibration** (Section 6) to ensure that the experimental stripes are centred on the stripe positions.
7. Follow the steps in Section 7.2 for optimizing the spectrum display.
8. Carry out the Alignment Check procedure described in Section 5 to ensure that the noisy signal is not caused by a minor optical misalignment.

9.3 FSR Crosstalk (weak spectral features observed close to strong peaks)

The crossed dispersion nature of the spectrometer can introduce minor artifacts when the spectrum is unwrapped. The origin of these features is discussed in Appendix E. If you observe a weak spectral feature *precisely* one or more etalon FSRs from a strong spectral peak, then you may be seeing FSR crosstalk (FCT). If the weak feature is not *precisely* one or more FSRs from the strong feature, it is almost certainly a real spectral component of the light source.

Appendix E explains the cause of the FCT feature and provides techniques to reduce its intensity relative to the nearby strong feature. Some of the common techniques are described briefly below for convenience, but refer to Appendix E for more details.

1. First, confirm that the suspected FCT features are precisely n^* FSRs away from the nearby strong spectral features.
2. Ensure that the input image is not overly saturated.
3. Carry out a **Quick Calibration** (Section 6).
4. Vary the values of the Gaussian Stripe Width (Settings Window) in the unwrapping process to minimize the intensities of the FCT features relative to the strong real features (See Section 7). Always click **calculate stripe overlay** after any changes in settings.
5. Carry out the Alignment Check procedure described in Section 5 to ensure that the noise in the signal is not caused by a minor optical misalignment. In particular, if the FCT is highly asymmetrical, it is likely to be caused by optical misalignment, unless caused by improper calibration.

6. Adjust the imaging lens as described in Section 5.

9.4 Weak Signal

The input source signal is too weak to perform a calibration or to take an accurate spectrum reading.

Troubleshooting steps:

1. Increase the gain and the exposure until the signal is clearly visible.
2. Check that the fiber optic cable types match (SMF connected to SMF, FC/PC to FC/PC). If the source output is APC, use an APC-to-PC hybrid patch cable.
3. Clean all fiber tips between the source and the spectrometer fiber optic input port - use a fiber microscope to verify that they are not damaged.
4. Carry out the Alignment Check procedure described in Section 5 to ensure the loss of signal is not caused by a minor optical misalignment.
5. If you are using a non-laser source, use an MMF fiber optic cable to achieve optimal signal if your spectrometer model supports it.
6. Temperature changes and physical displacement of the spectrometer can cause the stripe positions on the sensor to drift slightly. In either case, perform a **Quick Calibration** (Section 6) to correct the signal.

9.5 Moiré Fringes

If you have a broadband source coupled to the spectrometer and ring-like patterns are observed when you zoom in and out of the Camera window, do not be concerned. These rings are a type of Moiré fringe produced by the interaction of the sensor pixels and the pixels in the monitor display. The alternating intensities of the stripes can “beat” with the limited number of pixels available in the monitor display. Figure 9-1 contains an example.

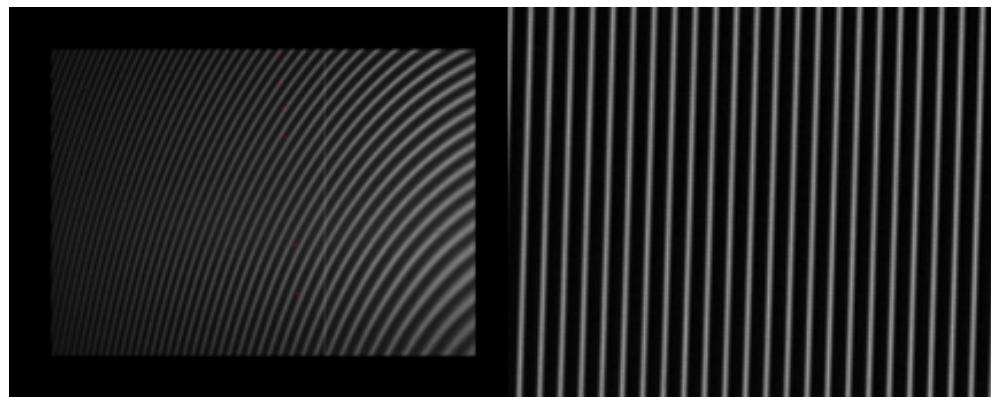


Figure 9-1 Moiré fringes, camera image zoomed out (left) and zoomed in (right).

An LED was coupled to the spectrometer and the Camera Window was opened in the SpectraLoK software. Moiré fringes are clearly observed in the left image, but they do not affect the spectrometer performance in any way. The right image is a magnified view of the left

image, and the Moiré fringes disappear as more monitor display pixels are now available for each stripe.

Section 10 - Appendices

Appendix A - Principle of Operation and Calibration of LightMachinery Spectrometers

A spectrometer is an optical instrument designed to split light into separate colors, or wavelengths. Thus, white light directed into a spectrometer will be separated into red, green, yellow, and blue light at the exit of the spectrometer. The ability of a spectrometer to separate closely spaced wavelengths is called the resolving power, R^1 , of the instrument.

For high-resolution spectrometers, Fabry-Perot (F-P) etalons provide a compact and cost-effective method to separate closely spaced wavelengths. Figure 1 explains the principle of the F-P interferometer².

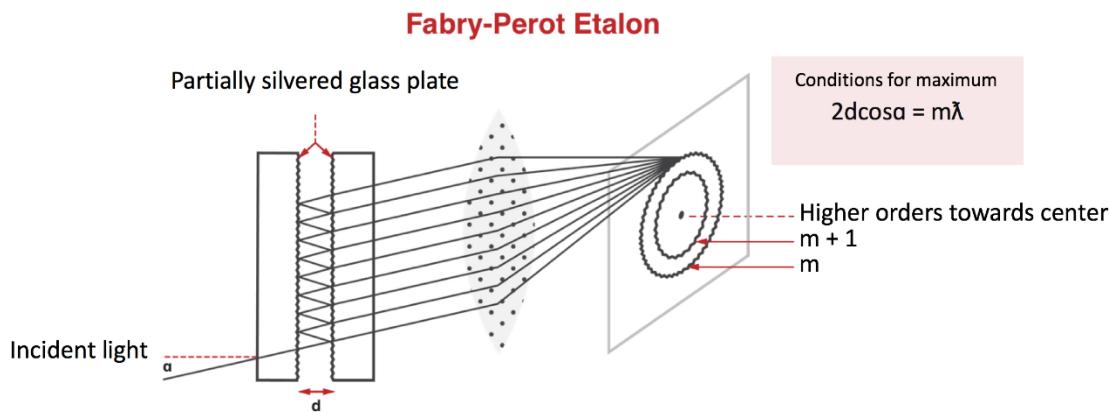


Figure 10-1 Principle of operation of an F-P interferometer, with the condition for the transmission maximum of the interference pattern³.

Note that the condition for maximum transmission of a particular wavelength, λ , is that a round-trip between the etalon plates must be exactly an integral number (m) of wavelengths. When the illumination source for the etalon provides a range of incident angles, circular fringes are formed at the focus of the lens. If the plate separation, d , is 0.25 mm, then a round trip is equal to $1,000\lambda$ at 500 nm, and it is easy to show² that it is possible to achieve $R \sim 50,000$ with a high-quality etalon with a 0.25 mm plate separation using sufficiently reflective coatings.

While F-P etalons provide high resolution, they suffer a significant drawback - the problem of overlapping orders. In the example above, light of wavelength 500 nm is transmitted through the 0.25 mm etalon because **exactly 1000** wavelengths fit into a round-trip in the etalon. However, light with a wavelength of 500.5 nm will also be transmitted through the etalon, this time with **exactly 999** wavelengths in a round-trip. The measurement system cannot distinguish between these two wavelengths, which are termed overlapping orders (order #999 and #1000, in this case). The problem of overlapping orders is further illustrated in Figure 10-2 for wavelengths near 550 nm.

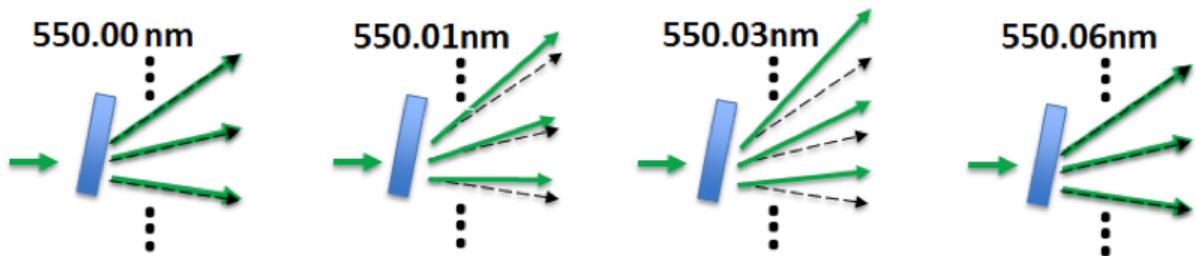


Figure 10-2 Three adjacent orders transmitted by an etalon as the wavelength of the incident light is tuned in steps from 550.00 nm to 550.06 nm.

Note that the etalon in Figure 10-2 cannot distinguish between light at 550.00 nm and 550.06 nm. The separation of these two wavelengths, 0.06 nm or 60 pm, is termed the Free Spectral Range (FSR) of the etalon and corresponds to a glass etalon with a thickness of 1.68 mm².

Fortunately, for an etalon illuminated using a cylindrical lens the various orders and wavelengths are dispersed⁴ only in the vertical direction. Hence, adding a cross-dispersing element that provides dispersion in the horizontal direction can separate the overlapping orders. The resolution in the horizontal direction needs only be sufficient enough to separate the adjacent orders. In the LightMachinery spectrometers, the cross dispersion is provided by a diffraction grating (reflective or transmission), as illustrated in Figure 3 for the case of a reflective grating.

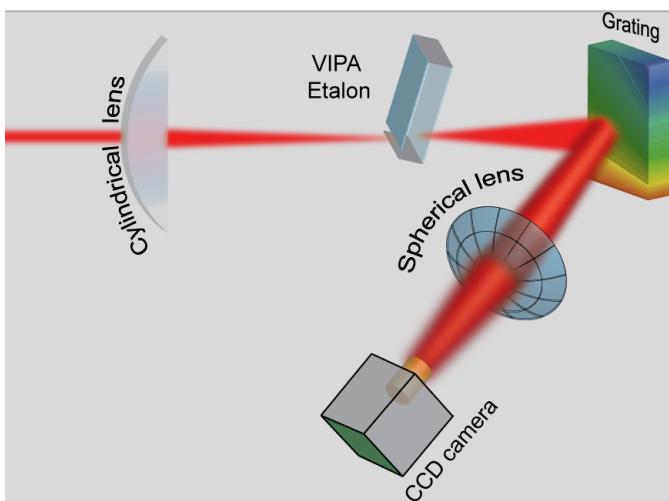


Figure 10-3 Schematic layout of the optical components in a LightMachinery spectrometer superscript 5.

The etalon in Figure 10-3 disperses the incident light in the vertical direction, providing a high resolution, but also overlapping orders. The grating separates the overlapping orders in the horizontal direction.

With the etalon and grating providing dispersion in the vertical and horizontal directions respectively, a lens assembly can be used to focus all the different wavelengths onto the surface of the camera sensor. The lens converts angles (in vertical and horizontal directions) into positions on the sensor array at the focus of the lens. Figure 10-4 illustrates the cross-dispersed spectrum as seen by the camera.

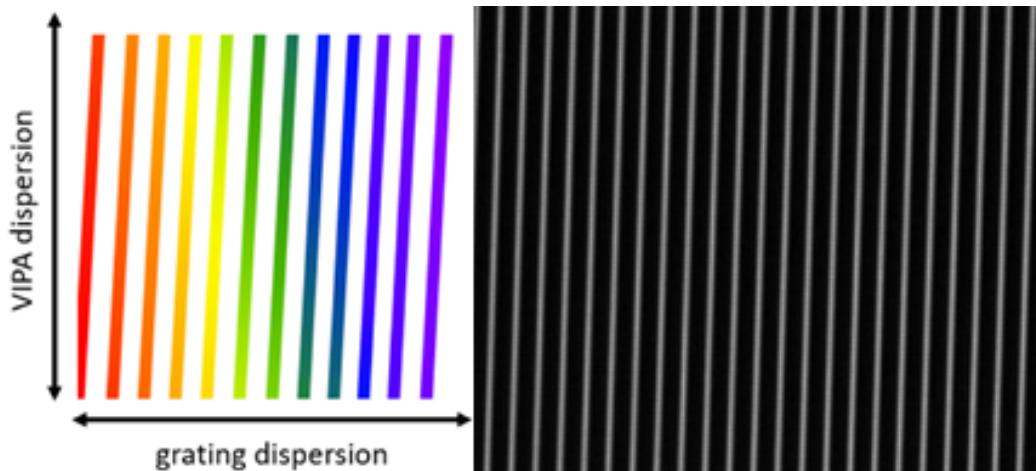


Figure 10-4 Schematic of the display expected at the camera when the crossed etalon and grating are illuminated with broadband (“white”) light.

In the vertical direction, the etalon provides high resolution, but only for a range of a few FSRs. In Figure 10-4, red represents longer wavelengths; blue shorter wavelengths. In the horizontal direction, the grating separates the overlapping etalon orders to allow the entire high-resolution spectrum to be unwrapped. Thus, the vertical stripes are spaced by one FSR in the horizontal direction. A typical screen shot taken from a small portion of the sensor is shown on the right.

Thus, the LightMachinery spectrometer combines high resolution (provided by the etalon) with an extended measurement range (provided by the grating)⁶. However, before the high-resolution spectrum can be displayed, the spectral information on each stripe must be decoded, and successive stripes stitched together. This process is called “unwrapping”, and is described in Appendix B1.

This Appendix is a shortened version of a LightMachinery White Paper that can be found at:
<https://lightmachinery.com/media/1857/hyperfine-principles-of-operation.pdf>

The generic term “etalon” is used throughout this Appendix. However, LightMachinery spectrometers can be equipped with either conventional Fabry-Perot etalons, or with specialized VIPAs (Virtually Imaged Phased-Arrays⁷). More than one order of magnitude increase in light throughput is obtained by switching from a F-P etalon to a VIPA etalon, as explained in the link above.

References and footnotes

1. If two wavelengths λ , and $\lambda + \Delta\lambda$, can just be separated (or resolved) by a spectrometer, the resolving power of the spectrometer, R is defined by:

$$R = \lambda / \Delta\lambda$$

Hence, a spectrometer operating at 500 nm with $R = 10,000$ can just separate two wavelengths that are spaced by 0.05 nm or 50 pm.

2. The link below provides an introduction to Fabry-Perot etalons:
https://en.wikipedia.org/wiki/Fabry–Pérot_interferometer

A calculator for F-P etalons can be found at the link below:

<https://lightmachinery.com/optical-design-center/etalon-designer/>

3. Reprinted from:
<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/fabry.html>
4. Gratings and etalons separate the incident light into its components by ensuring that different wavelengths emerge at different angles – this variation in angle with wavelength is called dispersion.
5. Reprinted from:
Van den Berg, Steven A., et al. *Scientific reports* 5 (2015): 14661.
6. The crossed-dispersion feature of the LightMachinery spectrometer is similar to that used in spectrometers based on echelle gratings.
7. A detailed description of VIPAs can be found at the link below:
<https://lightmachinery.com/optical-design-center/library/users-guides/vipa-designer-users-guide/>

A VIPA calculator can be found at the following link:

<https://lightmachinery.com/optical-design-center/more-optical-design-tools/vipa-designer/>

Appendix B1 – Spectrum Unwrapping Process in LightMachinery Spectrometers

In order to unwrap the spectrum of any arbitrary light source, the exact position of all the stripes on the sensor must first be mapped. The SpectraLoK calibration procedures are used to carry out this mapping process. The SpectraLoK software uses a physical model to predict the expected positions of the stripes, compares the predictions with the actual experimental positions, and refines the model to minimize any differences. The model is based on the equations describing the vertical dispersion provided by the etalon, and the horizontal dispersion provided by the grating.

All the relevant physical properties of the particular spectrometer (such as etalon thickness and lines/mm on the grating) are entered into the physical model. In general, the physical properties of each instrument are known accurately enough to allow the model to initially provide a very good map of the stripes over the entire sensor. The experimental calibration procedures allow the model parameters to be slightly modified (usually by less than a few percent) to provide a more exact fit to the experimental stripe positions. Once the spectrometer is properly calibrated (full details of the calibration process are provided in Section 6), the stripe positions predicted by the physical model are compared with the exact experimental stripe positions. Each predicted stripe position is then corrected by a polynomial equation to give a more exact match to the experimental stripe position (typically to better than one pixel in the X-direction). Finally, the result of the entire calibration process is recorded in a Look Up Table, LUT. The image from any light source can now be quickly unwrapped using the LUT, and the spectrum displayed. The use of a LUT allows the processor-intensive calculations of the physical model to be carried out once, and then stored in the LUT, thus allowing a direct labeling of pixel intensities with exact wavelengths.

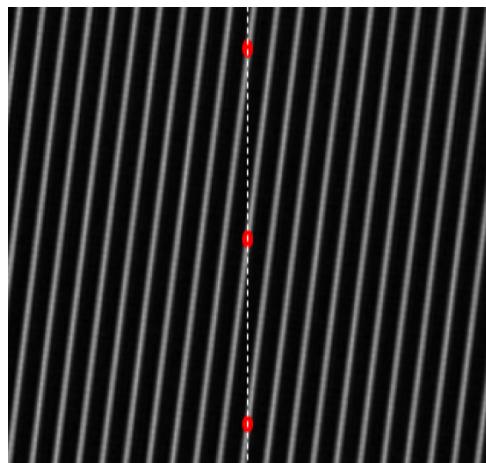


Figure 10-5 : A small portion of a typical image seen in the Camera Window of a spectrometer illuminated with broadband light.

The white stripes in Figure 10-5 must be unwrapped and stitched together to display the spectrum. The red blobs in Figure 10-5 indicate the image that would be obtained with a monochromatic source – three almost vertical blobs on adjacent stripes. Note that the same spectral information (the same wavelengths) occurs at different Y-positions on adjacent stripes.

Figure 10-6 shows close-ups of a few stripes to illustrate the process used by the SpectraLoK software to unwrap the spectrum.

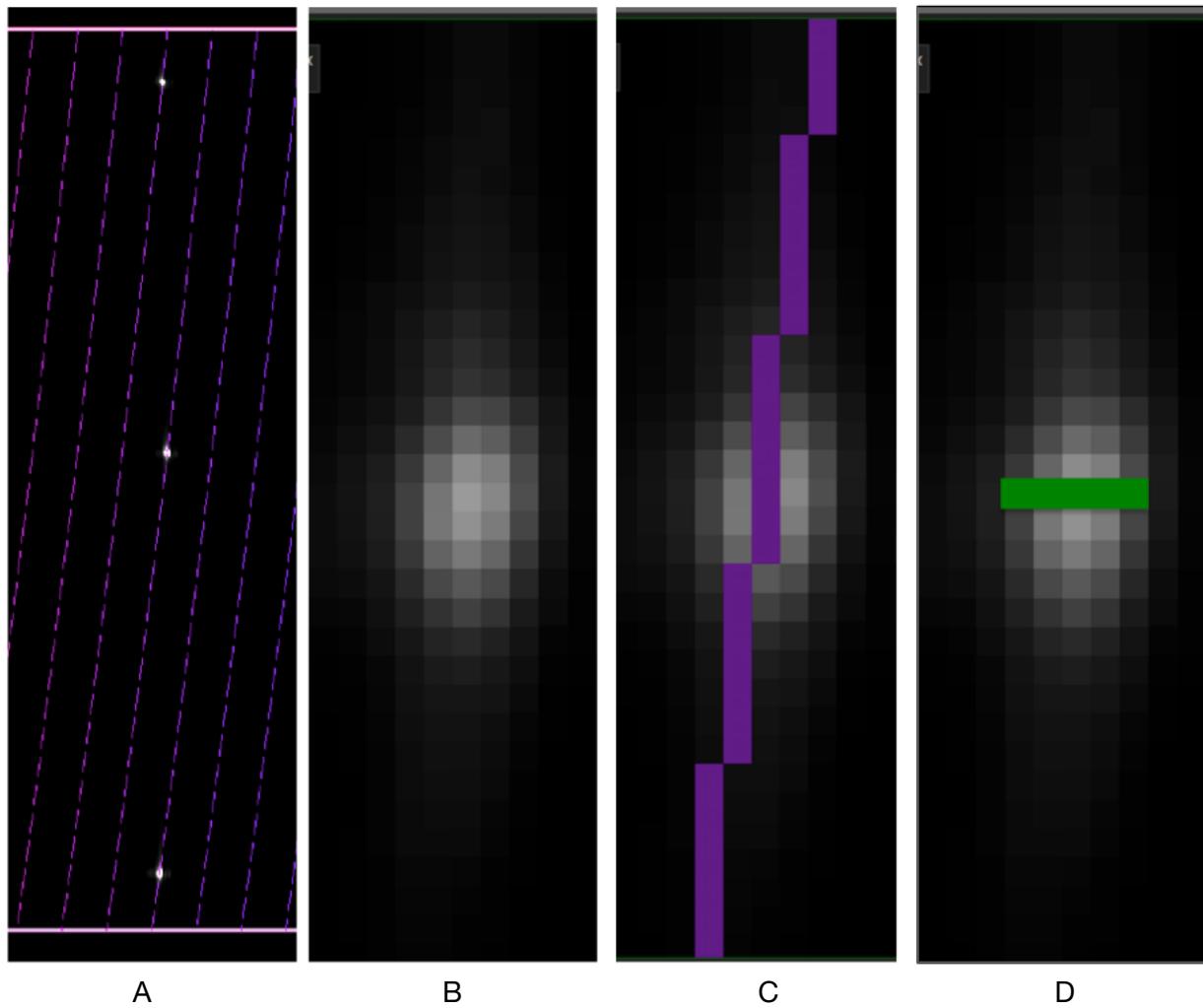


Figure 10-6 A series of images used to illustrate the SpectraLoK unwrapping process.

For the images in Figure 10-6, the spectrometer input is the light from a monochromatic laser at 532 nm. Figure 10-6A shows three blobs associated with the narrowband spectral feature at 532.00 nm, and the stripe positions predicted by the LUT. Figure 10-6B is a close-up of one of the blobs. In Figure 10-6C, the LUT predictions for the stripe positions are indicated in purple. The three blobs in Figure 10-6A fall on adjacent stripes, and hence three separate stripes must be unwrapped and combined to produce the final spectral display.

To unwrap an individual stripe, the SpectraLoK software first looks at every Y-position from the top of the stripe to the bottom, and uses the LUT to determine the exact X-position of the stripe peak intensity, and the exact wavelength for each Y-position. As the stripe intensity is usually spread over several pixels in the X-direction, the intensity, I , at each Y-position is best determined by averaging over several pixels in the X-direction. The “Gaussian Stripe Width”

parameter is used to define the range of pixels that are averaged in the X-direction to determine the intensity, I . In Figure 10-6D, a green rectangle indicates the pixels used in the average at one Y-position when the “Gaussian Stripe Width” parameter is set to 5 pixels (if the “Gaussian Stripe Width” parameter is set to none, then I is set to the value of the central pixel in the stripe). The process of averaging over a few pixels in the X-direction can lead to a significant improvement in the Signal-to-Noise ratio by accounting for the finite width of the experimental stripes, and reducing the effects of the discrete pixels (the discrete size of the pixels can cause pixel noise or pixel modulation in the unwrapped spectrum). The averaging process results in a reduction in the value of I (and a similar reduction in the noise) at each wavelength. In general, the “Gaussian Stripe Width” parameter should be set to the approximate width of the stripes (available values are 1, 3, 5, or 7 pixels).

Once the averaging in the X-direction is completed, SpectraLoK returns a (Wavelength, Intensity), or (λ, I) , pair associated with each Y-position on the stripe (typically >1000 pairs of data per stripe). This process is repeated for every stripe across the sensor. As can be seen from Figures 10-5 and 10-6, adjacent stripes contain overlapping spectral information – the same spectral feature appears at different Y-positions (but at the same wavelength) in different stripes. Hence, the SpectraLoK software next sorts all (λ, I) pairs by wavelength. Figure 10-7 shows a plot of Intensity versus Wavelength for three adjacent stripes, as derived from the intensity in Figure 10-6A.

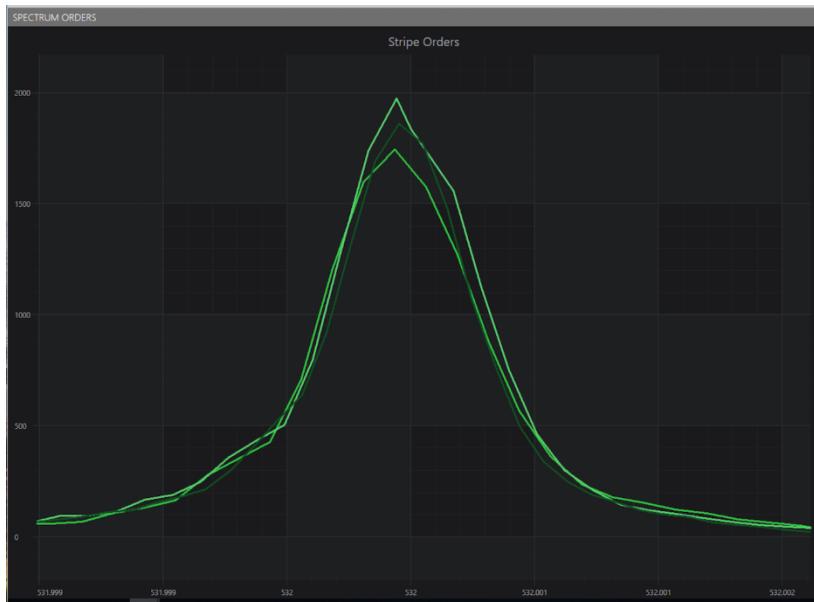


Figure 10-7 (λ, I) pairs retrieved from three adjacent stripes, after sorting by wavelength.

Figure 10-7 displays the (λ, I) pairs from three different blobs with slightly different peak intensities. Different colours are used to represent the unwrapped (λ, I) pairs from the three adjacent stripes. (The “jagged” nature of the plots corresponds to the individual pixels in the Y-direction). The software next combines the data from different blobs by placing the (λ, I) pairs into separate “bins” along the wavelength axis. The size of the bins (in pm) is determined by the value of the Display Increments parameter in the Settings Window. Typically, the Display

Increments parameter is set to 0.2 times the instrument resolution. The software also allows the option of applying a sliding Gaussian average to these wavelength bins, as determined by the value of the Gaussian Smoothing parameter.

The resultant Intensity versus Wavelength plot is displayed in the Spectrum Window, as shown in Figure 10-8.



Figure 10-8 The data from the images in Figure 10-7 are displayed in the Spectrum window after unwrapping by the SpectraLoK software, combining the (λ, I) pairs from three adjacent stripes, and smoothing with the Gaussian smoothing parameter.

Further information on the unwrapping parameters, and procedures for calibrating and optimizing the displayed spectrum can be found in Sections 4, 6 and 7.

Appendix B2 - Spectrum Unwrapping and Calibration for Spectrometers that ship with an External Etalon Module.

In 2022 LightMachinery introduced a novel technique for calibrating the etalon-based cross-dispersion spectrometers described in this manual (the new calibration technique replaces the physical model approach described in Appendix B1). The new calibration technique relies on a second etalon that is placed in the beam of a broadband source external to the spectrometer. The light transmitted through the etalon is coupled to the spectrometer for calibration purposes. Figure 10-9 shows a typical **Dot image, or the Etalon Modulated image** together with the spectrum obtained after unwrapping the image.

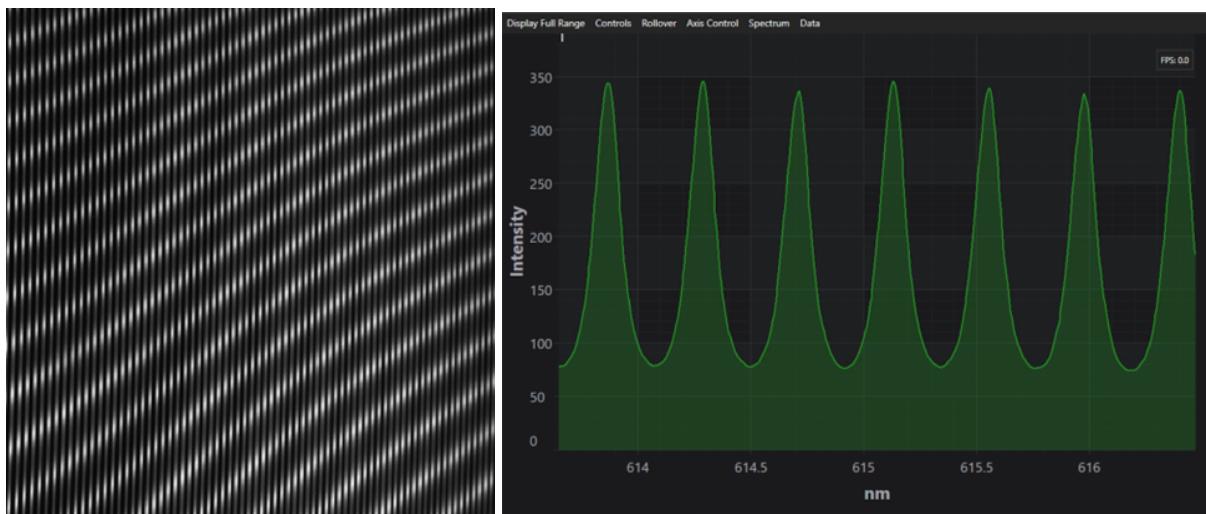


Figure 10-9. A typical image obtained when an external etalon modulates the light from a broadband source. A portion of the unwrapped spectrum is shown on the right – a series of equally-spaced transmission peaks separated by the FSR of the calibration etalon.

An ideal calibration etalon would have two mirrors separated by an optical spacing that is constant at all wavelengths. Such an etalon would have an FSR (measured in GHz) that is constant with wavelength, resulting in a very straightforward calibration process. However, calibration etalons are usually made of fused silica with a refractive index (and hence optical pathlength) that varies with wavelength. The optical coatings of the mirrors also add an additional wavelength-dependent contribution to the optical path-length between the two etalon mirrors. Fortunately, the refractive index of fused silica is well-known as a function of wavelength, and the coating contribution to the FSR can easily be calculated. Hence one can predict the variation of FSR with wavelength, as shown in Figure 10-10.

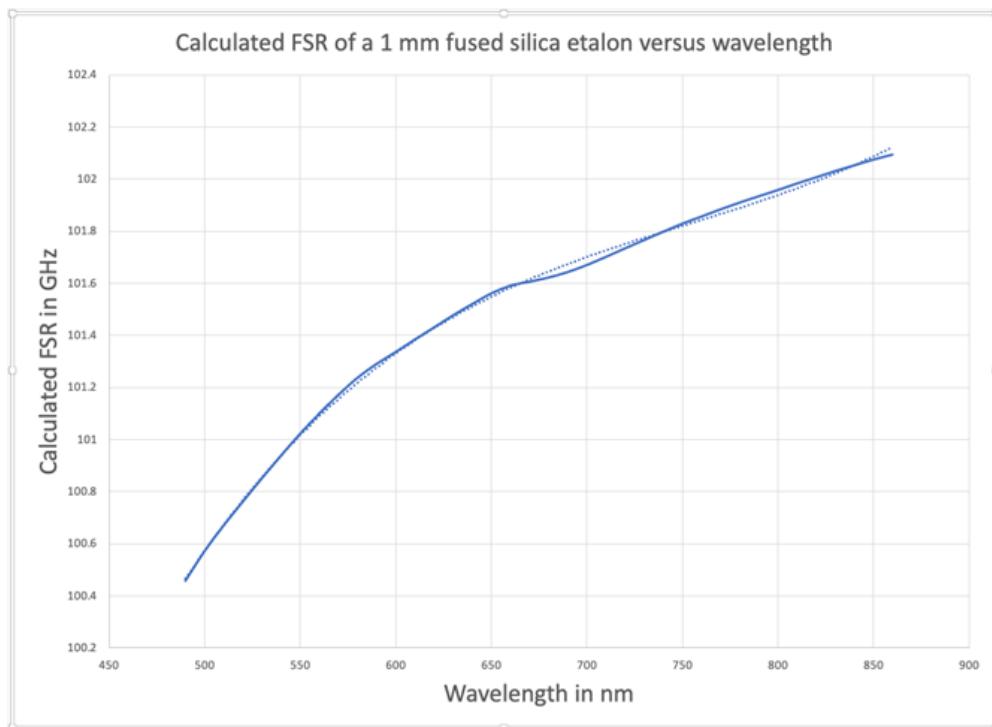


Figure 10-10 – The blue line shows the calculated FSR. Both the variation of refractive index of fused silica and the variation of optical thickness of the mirror coatings are included in the calculation. The dashed line is a polynomial fit to the blue data, and the polynomial coefficients are used in the calibration routine.

Note that the FSR changes by less than 2% percent over the entire wavelength range, and this small change is accurately known. LightMachinery makes several calibration etalons with differing thicknesses. The FSR variation of each etalon is calculated and then separately checked using known reference lines from Hg/Ar and Neon lamps before the etalon is placed in the calibration unit. These etalons with known FSR curves can now be used to calibrate a spectrometer, as described in detail in Section 6.4. While conventional spectrometers are usually calibrated by a few lamp or laser lines (at most), LightMachinery spectrometers can be calibrated by hundreds of etalon transmission peaks. This approach allows a “wavelength map” to be created of the entire sensor surface which automatically accounts for any slight non-linearities in the optical components of the spectrometer (the internal etalon / VIPA dispersion or the grating dispersion) that cannot be predicted from the physical properties used in Appendix B1. This wavelength map is used to record a Look Up Table, or LUT, in the same fashion as described in Appendix B1 (where the physical properties of the spectrometer were used to record the LUT).

Once the LUT is recorded and saved in the Configuration File, the process of unwrapping the sensor image to generate the spectrum proceeds exactly as described in Appendix B1. Figure 10-11 illustrates the quality of the wavelength calibration that can be attained using the hundreds of reference wavelengths provided by a calibrated external etalon.

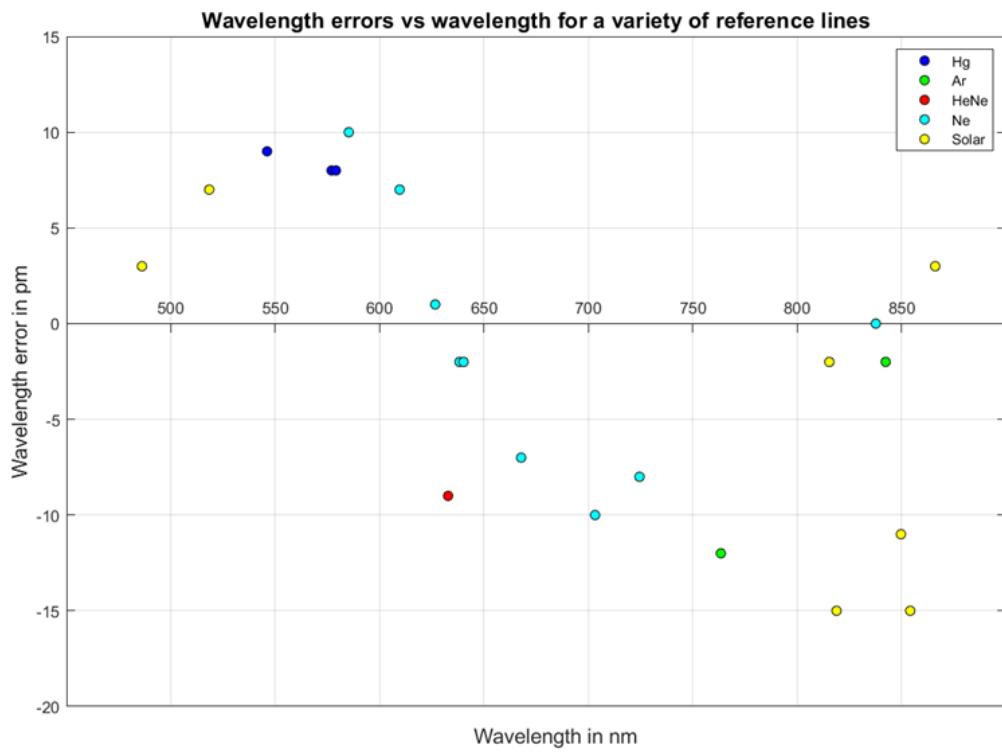


Figure 10-11. Measured wavelength accuracy of an HN-9332-UHR spectrometer after calibration. Each data point represents a separate reference source (lamp and laser emission lines, and solar Fraunhofer absorption lines). The wavelength error is the difference between the measured wavelength and the literature value for the source.

In addition to providing excellent wavelength accuracy, the calibration process also ensures that the (λ, I) pairs from adjacent stripes overlap exactly in wavelength, as illustrated in Figure 10-12.

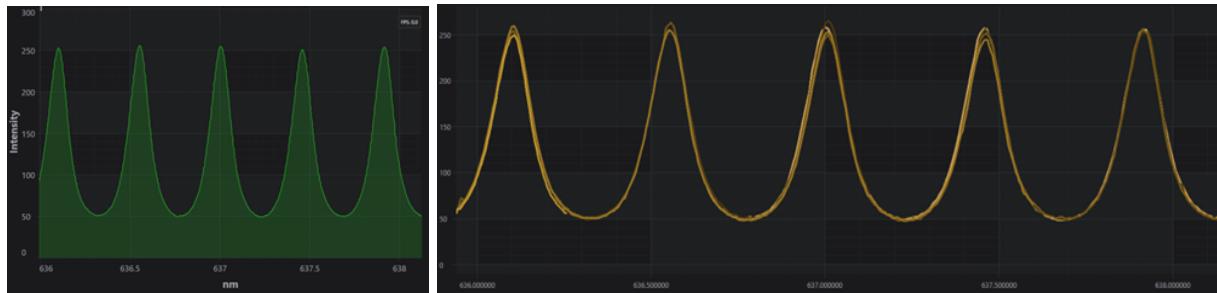


Figure 10-12. The screenshot on the left shows the normal unwrap of 5 etalon peaks in the 637 nm region, while the right screenshot shows the separate contributions from 5 adjacent stripes (the spectrum from each stripe is shown in a slightly different color).

The key to a successful calibration is to ensure that the contributions from each stripe overlap almost exactly. This is the case in Figure 10-12, but occasionally the calibration procedure is not ideal, and etalon peaks from different stripes are **separated** in wavelength, as shown in Figure 10-13.



Figure 10-13. Etalon peaks from five different stripes superimposed. Note the slight variation in central wavelength from stripe to stripe. The maximum variation is shown by the two arrows and is defined as the **separation** for this series of five dots.

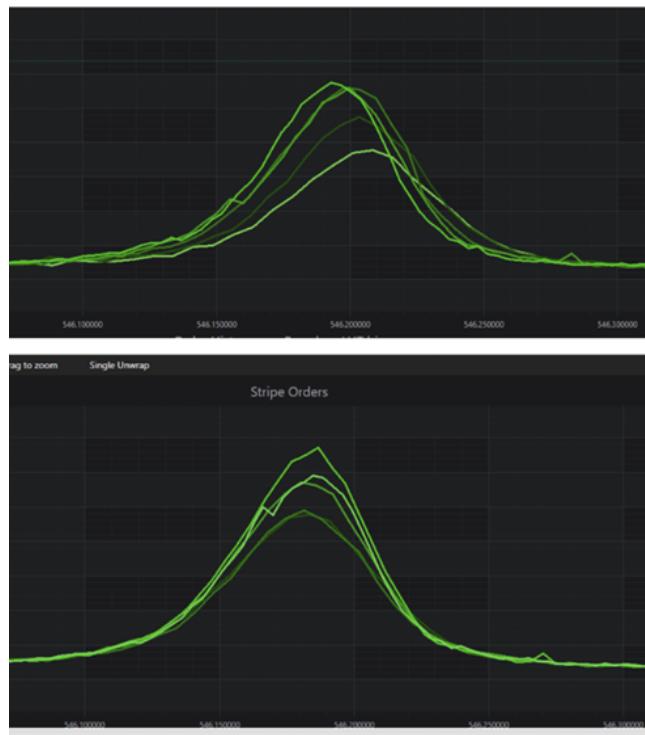


Figure 10-14. Comparison of the spectra from two different dots – one with significant **separation**, and one with minimal **separation** between the spectra from different stripes.

As described in Section 6.4.3, the Mapping Calibration process reports results in terms of the average and worst-case separation, and compares these results with the nominal instrument resolution, allowing any possible degradation in resolution due to the calibration process to be easily identified.

Appendix C – Examples of Narrowband Sources for Etalon Calibration

As discussed in Section 6, in order to calibrate the etalon dispersion, a light source is required that has one or more narrowband spectral features within the wavelength range captured by the sensor. The narrowband source can be a single-mode laser, a multimode laser (with distinct, separate features), or a spectral/arc lamp with narrowband features. Ideally, the narrowband spectral features will have a line-width less than the resolution limit of the spectrometer (typically between 1 and 25 pm, depending on the model). At the very least, the narrowband source **must** be significantly narrower than the etalon FSR (typically between 45 and 2000 pm, depending on the model). The calibration procedure described in Section 6 requires the user to manually select a series of blobs (see below) associated with the same spectral line. The selection process is simple but may require some practice.

This Appendix contains sensor images obtained with a variety of narrowband sources and gives examples to help with the selection of blobs for calibration purposes. Figure 10-15 below illustrates the ideal source – a truly monochromatic laser source with negligible line width. In this case, there is no ambiguity in choosing the correct series of blobs.

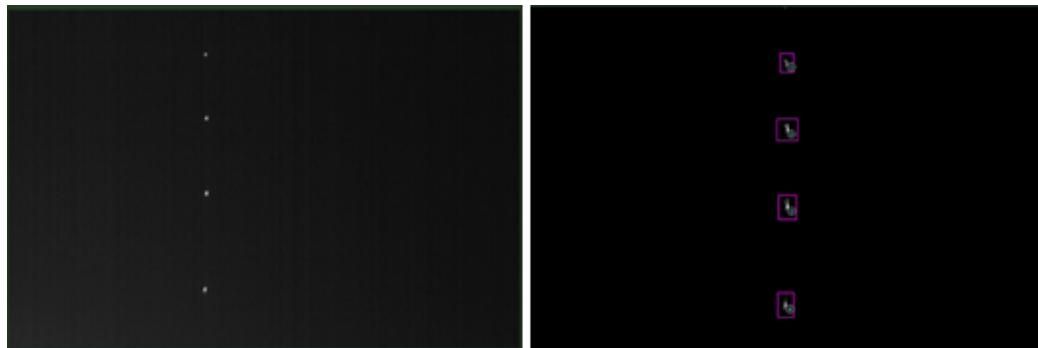


Figure 10-15 The images show the blobs recorded when the light from a single frequency laser is input to a LightMachinery spectrometer. The full width of the sensor is equivalent to ~30 nm, and the laser operates at 1064 nm.

The image on the right in Figure 10-15 shows the 4 blobs selected prior to the **Etalon Calibration**.

The blobs in Figure 10-15 have been over-saturated for better visibility in the Figure. However, for the **Etalon Calibration** procedure, all the blobs should be correctly exposed as explained in Appendix F. (The blobs in the series are selected in the SpectraloK software by drawing a rectangular box around each blob in turn - press the Control key and then right click and hold on the center of each blob. Next, draw a rectangle around each blob before releasing the right

mouse button. Each rectangle should encompass all the pixels containing intensity associated with the blob, but not include any pixels containing intensity from nearby spectral features. When the blobs are isolated, as in Figure 10-15, an alternative selection process is simply to right click on the center of the blob with the “Box width and height” parameters set to appropriate values. *Take care to select the blobs in sequence, do not omit a blob, nor select the same blob twice).*

The next two images in Figure 10-15 were all taken with an Hg-Ar lamp illuminating the spectrometer. Spectroscopic arc lamps generally provide narrowband spectral features at a wide range of wavelengths from the IR to the UV.

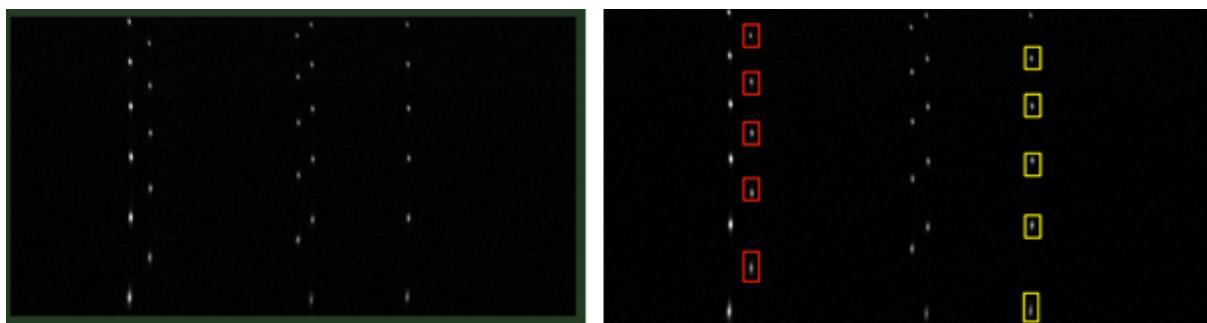


Figure 10-16 Images from a Hg lamp recorded by a LightMachinery spectrometer.

In Figure 10-16, the image on the left shows the blobs recorded when the light from an Hg lamp is input to a LightMachinery spectrometer. The Argon lines range from 811.5 nm to 794.8 nm. There are five different series of blobs that are suitable for Etalon Calibration. The image on the right identifies two different series with red and yellow rectangles. Note that a series can contain five or six blobs as the sensor spans 5+ FSRs.

Take care to only select *one* series of blobs - either the yellow series or the red series, for example. Try to avoid blobs that are very close to the edge of the sensor or ensure that the selected area is completely within the sensor boundary. To ensure the best calibration of the wavelength scale of the spectrometer, choose a series of blobs for which the wavelength is accurately known.

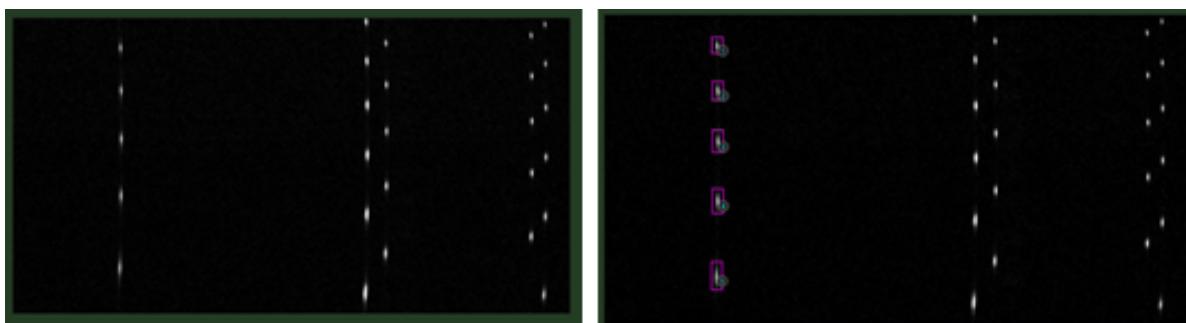


Figure 10-17 Additional Hg lamp features with one series of blobs selected using the SpectraLoK software prior to Etalon Calibration.

Figure 10-18 is taken with a multi-mode laser illuminating the spectrometer. This type of laser is generally inexpensive, operates in a narrow wavelength range, and can be purchased to operate throughout the visible and IR regions.

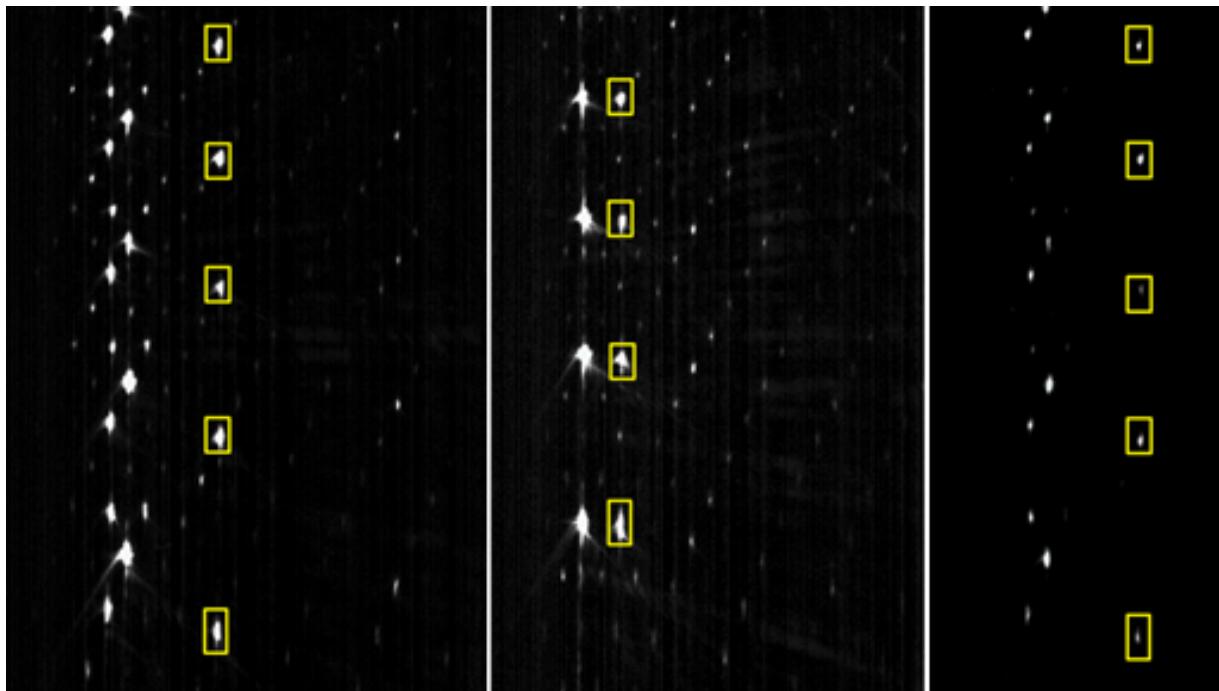


Figure 10-18 Three successive images recorded with a 950 nm multi-mode laser input to the spectrometer. Possible blob series for calibration are identified with yellow rectangles. Some blobs are over-saturated for better visibility.

As seen in Figure 10-18, the wavelength distribution of multimode lasers can often change dramatically on a short timescale. Hence, it is recommended that one image is captured, the blob series is selected, and then the **Etalon Calibration** is carried out, all on the same image (ensure the **Use current image** slider is enabled). As usual, it is important to use exposure and gain settings that do not produce saturation to any of the blobs selected. Successive **Etalon Calibrations** may require repeating these three steps.

Appendix D – Manual selection of etalon calibration points for weak sources

In general, the use of long exposure times and high values of Camera Gain enables weak sources to produce blobs with sufficient intensity on the sensor for an **Etalon Calibration**. For weak sources, background subtraction and averaging of successive images is recommended. However, there are occasions when the software is unable to identify the center of the weak blobs generated by very weak spectral lines. In these cases, the solution is to manually identify the center of each blob, as follows. Once the weak image of the spectral lines has been captured on the sensor, “zoom” into each of the blobs in turn (increase the Software Gain, if required, to increase the visibility of the blob) and with the “Box width and height” **set to 1**,

select the pixel at the center of the blob (in both X and Y directions), and right click on this pixel. A typical example is shown in Figure 10-19 below.

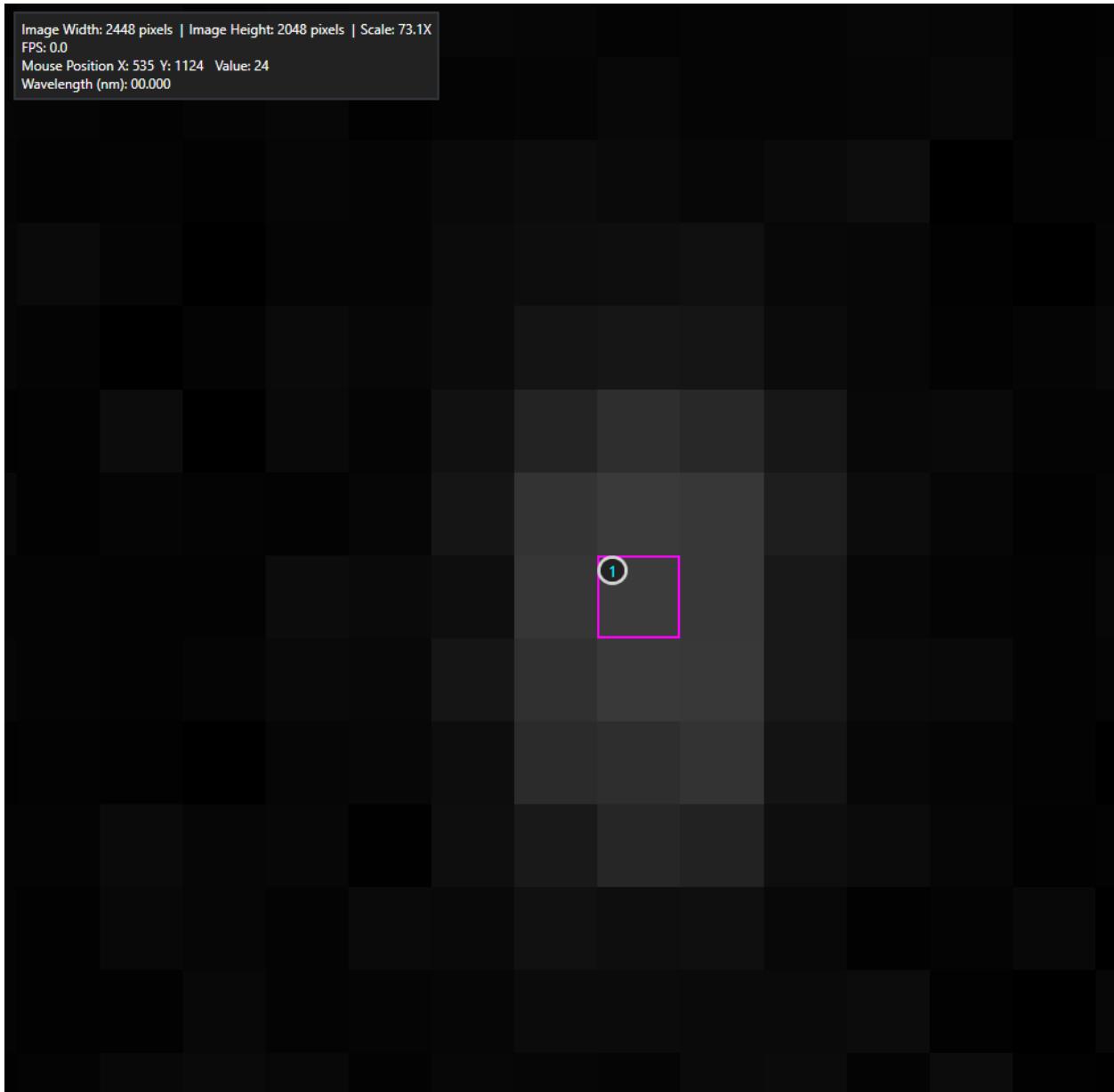


Figure 10-19 – Typical result after manually selecting the center of a weak blob

Repeat this process until all the blobs in the series have the centers manually selected, and after ensuring the **Use Current Image** slider is enabled, click on **calibrate etalon**. (Note that you can also use the manual identification strategy to perform an etalon calibration on absorption lines. Please contact LightMachinery for details).

Appendix E – FSR Crosstalk, Its Origin and Mitigation Strategies

LightMachinery spectrometers use an etalon and a grating to cross disperse the spectral content of the input light in the vertical and horizontal directions. One potential disadvantage to this configuration is that it can introduce minor artifacts, or crosstalk when the spectrum is unwrapped. The crosstalk presents as weak satellite features spaced exactly one or more etalon FSRs (Free Spectral Range) from any strong spectral features in the input signal. For this reason, the process that causes such features is referred to as FSR crosstalk or FCT. The intensity of any FCT feature is often insignificant (i.e., comparable to the background noise), but fortunately, FCT is typically straightforward to distinguish from true spectral components and to correct for. FCT can almost always be eliminated or discarded in post-analysis.

Origin and Identification of FCT

As described in Appendix A, the image captured by the spectrometer camera corresponds to the spectrum of the input light “folded” into many stripes adjacent to one another. Although the actual stripes are only observed when a broadband source is coupled to the spectrometer, any spectral features contained in the input light must *always* fall somewhere along these stripe positions.

Horizontally (grating dispersion direction), adjacent stripes are separated by precisely one etalon FSR. This follows from the fact that two wavelengths separated by exactly one etalon FSR will undergo constructive interference at the same vertical angles, and thus will be imaged onto the camera at the same vertical height, or Y-position, while being separated in the X-direction by the grating dispersion.

The width of the stripes depends on multiple factors - the resolving power of the grating, the horizontal width of the input (slit width or fiber core diameter), the camera pixel width, the focal length of the collimating and imaging lenses, and the aberrations of the optical system. Although the FWHM (full width at half maximum) of the stripes is designed to be significantly smaller than the stripe separation, the stripe intensity does not end abruptly at the FWHM, but rather extends in a near-Gaussian profile with weak (but sometimes extended) tails well beyond the FWHM. Optical aberrations and diffraction effects can extend these small tails in the horizontal profile of the stripes to beyond one stripe separation. These tails can result in crosstalk between stripes, and FCT features in the reconstructed spectra, particularly when a strong spectral feature is present in the input signal. *The SpectraLoK software will interpret any non-zero intensity at the adjacent stripe position as if the input light source truly contained this spectral feature.*

It is important to note that FCT features can only fall precisely n^* FSR away from the real feature where $n = \pm 1, \pm 2, \pm 3$, etc.¹. Figure 10-20 illustrates the formation of an FCT feature when a strong laser illuminates the spectrometer.

¹ In the case of a spectral feature that is broader than the resolution of the spectrometer, the ghost features must perfectly reproduce the shape of the real feature.

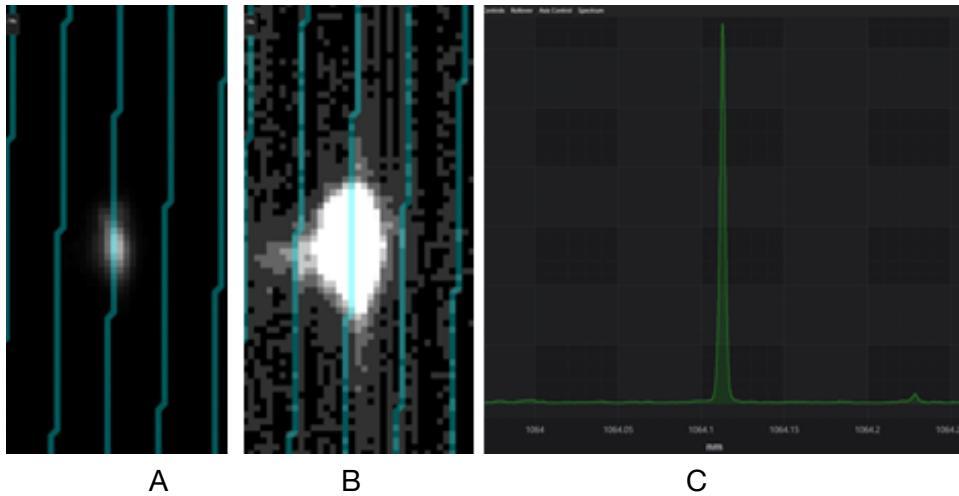


Figure 10-20 An illustration of the origin of FSR crosstalk, FCT.

In Figure 10-20A, a single-frequency laser illuminates the sensor at 1064.120 nm - a single blob is shown in the Camera Window, with the stripe overlay activated. In Figure 10-20B, the blob gain and exposure are significantly increased to show the faint wings of the blob. Note that some intensity “bleeds” onto the stripe to the left, which is at a longer wavelength. Figure 10-20C shows the unwrapped spectrum in the Spectrum Window. The faint blob wing at longer wavelength appears as an FCT feature at ~1064.235 nm or ~115 pm to the red of the main peak, corresponding to one FSR of the etalon.

Several techniques can be used to reduce the intensity of an FCT feature relative to the nearby strong feature:

1. First, confirm that the suspected FCT features are precisely n^* FSR away from the nearby strong spectral features. (Any spectral feature that does not *precisely* meet this specification is a real spectral component of the light source).
2. Ensure that the input image is not overly saturated. Strong saturation increases the relative intensity of any FCT. (Reducing the intensity of the pump source is not generally an option in applications such as Brillouin or Raman spectroscopy).
3. Carry out a **Quick Calibration** (Section 6). This calibration process ensures that the experimental stripe positions are centered on the positions predicted by the SpectraLoK model, and that the FCT is minimized.
4. Vary the values of the Gaussian Stripe Width in the unwrapping process to minimize the intensities of the FCT features relative to the strong real features. Smaller values for the Gaussian Stripe Width are usually better for minimizing the FCT (See Section 7).
5. Carry out the Alignment Check procedure described in Section 5 to ensure that the noise in the signal is not caused by a minor optical misalignment.
6. If the preceding steps do not reduce the FCT, the focus of the imaging lens may be non-optimal. A significant change in grating angle (some models only), vibrations, or rapid changes in temperature can cause a non-optimal focus. Adjust the imaging lens as described in Section 5.

Carrying out steps 2-6 should significantly reduce the intensity of the FCT features. If the remaining intensity is still a problem, steps 1-3 below offer techniques for mitigating the its effect:

1. Perform differential measurements when possible; this way, even if the signal contains a real weak spectral feature exactly n^* FSR away from a strong spectral feature, the weak spectral feature can be retrieved. For instance, in the context of Brillouin spectroscopy, record the spectrum before and after introducing the sample, and subtract the former from the latter (after proper rescaling if necessary). Even if the amplitude of the elastic scattering peak changes upon introduction of the sample, you can rescale it based on non-saturated portions of the spectrum. In certain instances, you can do this in real-time using the **Capture Background** option of the SpectraLoK software.

NOTICE

The real-time method can be used even if the signal amplitude changes, by adjusting the gain or exposure until the strong spectral feature is fully cancelled by the background subtraction.

2. Characterize the FCT profile using a single longitudinal mode laser immediately prior to performing your measurement and then subtract it (using appropriate scaling) from the measurement. This is equivalent to performing a differential measurement using a separate source. For this method to be effective, care must be taken to prevent motion of the input fiber and to minimize the time between the FCT characterization and the final measurement (to eliminate drifts due to changing temperature). The FCT profile is sensitive to both factors.
3. Perform a comprehensive image analysis. Based on the centroid or Gaussian fits of partially superimposed blobs recorded by the camera, it is possible to identify which stripe an individual feature is associated with. This makes it possible to recover a very weak signal that falls exactly n^* FSR away from a strong feature, even in cases where a differential measurement is not possible. Figure 10-21 contains an example.

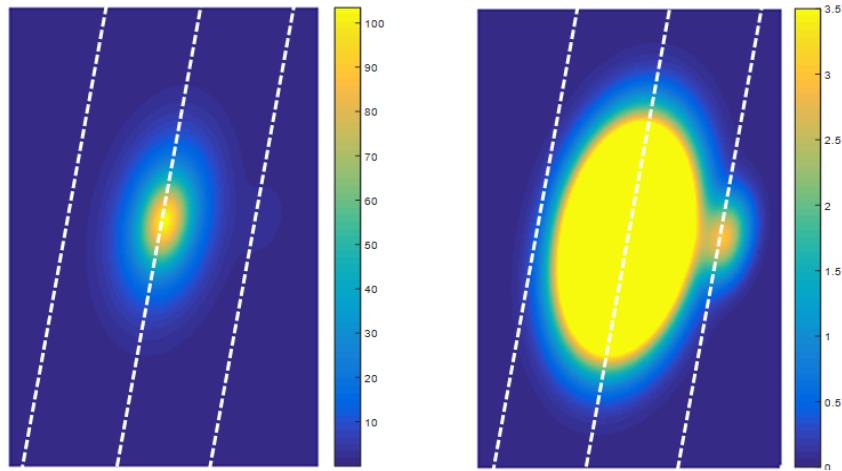


Figure 10-21 Simulated false color intensity map demonstrating the distinguishability upon image analysis of a weak spectral feature falling exactly 1 FSR away from a strong feature.

The intensity profiles are similar in both images, but the intensity scale was adjusted beyond saturation in the right image. Even if the amplitude of the weak right spot is on the same order of magnitude as the amplitude of the strong middle spot's tail, the weak spot could easily be extracted using basic image analysis. By properly fitting the horizontal cross section of the spectral features with a superposition of modified Lorentzian or Gaussian profiles, the FCT contribution can be subtracted out and the artifact-free spectrum retrieved.

NOTICE

If you need to analyze the raw images captured by the sensor, or have any questions about the above procedures, please contact LightMachinery.

Appendix F – Exposure, Gain and Saturation

For most applications of LightMachinery spectrometers, the key to obtaining the best spectrum from a given light source is to optimize the Camera gain and exposure settings to avoid saturation of the camera sensor (**notable exceptions being for Brillouin or Raman spectroscopy in which the elastic scattering signal will typically saturate**). This Appendix explains the optimization process in detail and is broken down into two sections – one for strong light sources and one for weak light sources.

Strong Light Sources

A strong light source is usually a laser and will generally allow sufficient light input to the spectrometer to produce strong signals on the sensor at relatively short exposure times. For most applications, the exposure and gain are optimized when the most intense spectral feature in the signal is just below the saturation level of the pixels in the sensor. All sensors have a limited dynamic range – the range over which they give a linear response of signal level versus light intensity. For a 12-bit sensor the linear response is limited to 0-4095 distinct integer levels¹. Once the light intensity incident upon a sensor pixel is sufficient to cause the pixel to record a level of 4095, any further increase in intensity does not produce any corresponding increase in sensor level output. This limiting, or flattening of response, is called *saturation*. In general, it is best to avoid any significant saturation in the sensor image, as saturation results in a non-linear spectral readout, and high levels of light could damage your sensor.

Optimizing the sensor exposure and gain can be either performed directly in the spectrum window, as summarized in Figure 7.2, or it can be performed in the Camera window, as described below. The camera can be opened by clicking on the Camera Icon in the SpectraLoK Window. Click **Capture** to enable a continuous feed of images from the camera, and then increase the exposure until the input light signal causes a few pixels to saturate, as shown in Figure 1. By default, the Camera window is set to indicate any saturated pixels in red². [Note that saturated pixels may not appear red if a background is being subtracted; if this is the case, you can either clear the background or you can toggle the **Internal Saturation Detection** and set the field **For intensity greater than** to the appropriate value (e.g. 4095 in the case of a 12-bit sensor).] Reduce the exposure to eliminate any saturated pixels (or to just leave the occasional saturated pixel). For optimal signal stability, it is best to use longer exposures in combination with lower gain, rather than short exposures with high gain. You may need to attenuate the light source physically (by using filters, for example) if saturation occurs at the camera's lowest exposure and gain settings - to optimize the signal stability, it can be beneficial to reduce the intensity of the source to allow an exposure >100 ms without saturation.

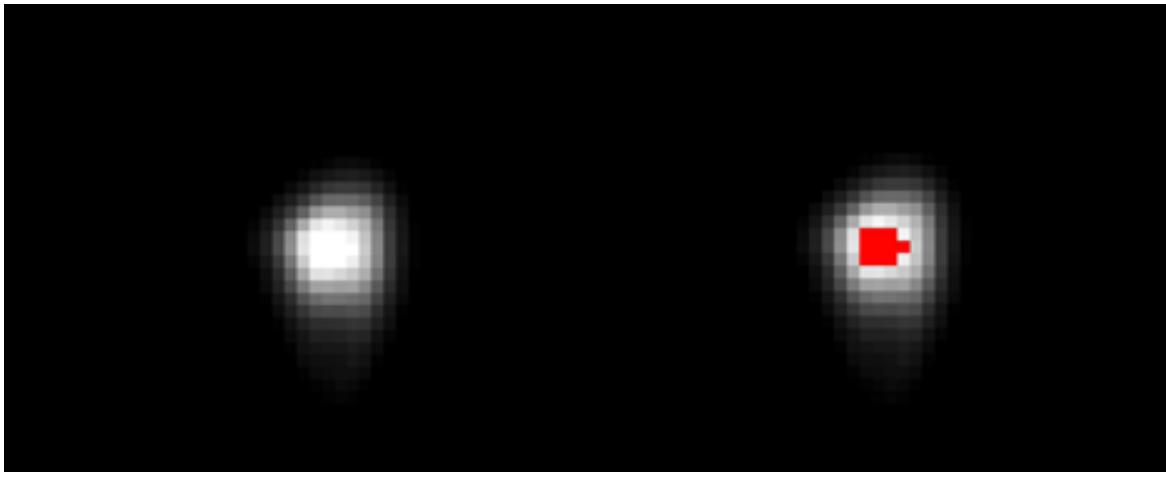


Figure 10-22 : A close-up of the sensor image of a blob from a single-frequency laser source with saturated pixels shown in red in the image on the right.

The intensity level of any pixel can be determined by right-clicking on the pixel position and reading the intensity in the bottom right of the Camera Window (see example in Figure 10-23). Clicking on the Mountain Icon next to the pixel will open a 3-D display of the nearby pixels, as shown in Figure 10-23.

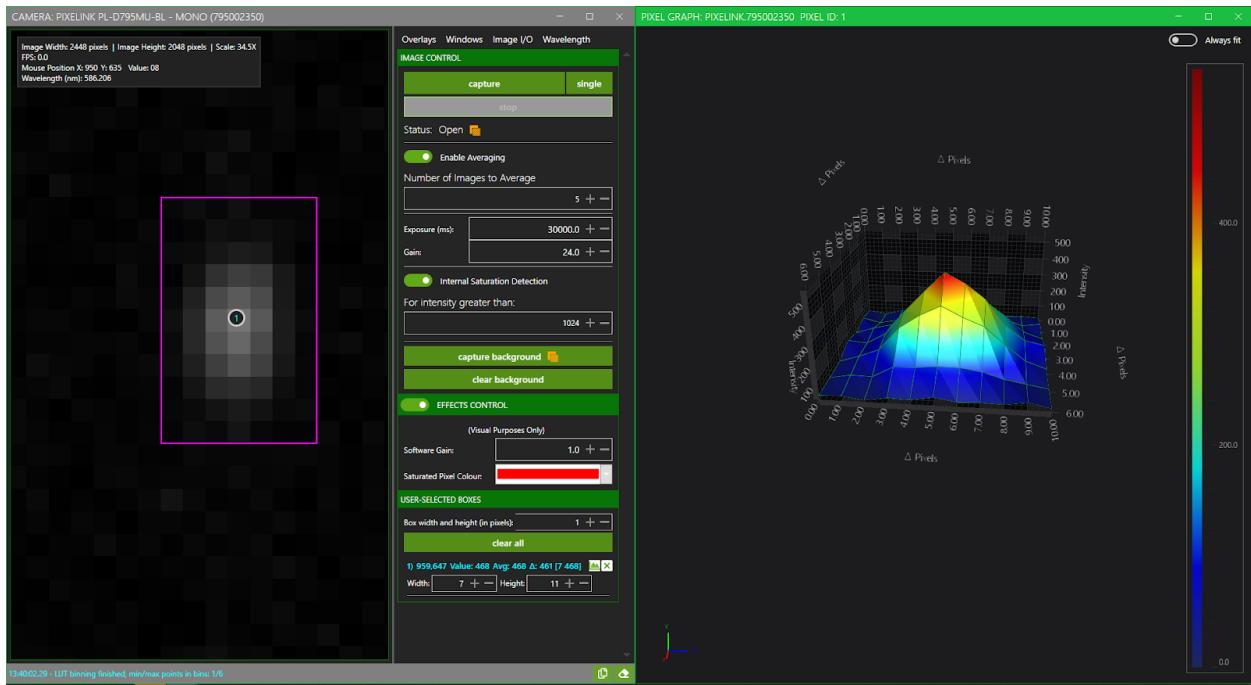


Figure 10-23 Intensity level of an individual pixel displayed in the Camera window, together with a 3-D display of the surrounding pixels. The area of the surrounding pixels is determined by the value of the “Box width and height” parameters.

Note that in Figure 10-23, the intensity of the selected pixel is 2874, and the average intensity in the surrounding square is 327.

With a strong light source, it is recommended to zoom into the most intense features in the sensor image to ensure a minimal number of pixels are saturating. The techniques illustrated in either Figure 10-22 or Figure 10-23 can be used for this purpose, and the exposure and gain set accordingly. The ideal exposure setting is one that results in signal levels of ~90-95% of the saturation level for the most intense pixels³.

In some applications (Brillouin and Raman spectroscopy, in particular) it is common to have a pump laser that strongly saturates the sensor in a limited region. For these applications, the goal is to ensure that the much weaker signal at the shifted frequency is optimized and does not cause saturation.

Once the exposure and gain have been optimized in the Camera Window, switch to the Spectrum Window to view the unwrapped spectrum (assuming Calibration has been carried out – see Section 6). If the intensity of the input light increases, it is possible saturation may occur⁴ and the exposure may need to be reduced (or increased in the event of a drop in light intensity). **Return to the Camera Window to reset the exposure**, as saturation may occur in the most intense pixels even if the intensity levels displayed in the Spectrum window are well below the saturation level⁴.

Weak Light Sources

A weak light source is typically a non-laser source such as an arc lamp, an LED, or a broadband source that has insufficient light input to the spectrometer to produce signals on the sensor that approach saturation, even at the longest exposure times and highest gain levels. With this type of light source, the optimization goal is to ensure the best Signal-to-Noise ratio, SNR, in the sensor image.

Optimizing the sensor exposure and gain are best performed initially in the Camera Window, which can be opened by clicking on the Camera Icon in the SpectraLoK Window. Click **Capture** to enable a continuous feed of images from the camera, and then set the **exposure** and **gain** to their maximum values (input very large values to each variable and the parameter will default to the maximum available for that particular camera). If the image now contains some saturated pixels, follow the procedures above to optimize the exposure and gain (Strong Signal). In the more likely event that the image is still very faint, increase the **Software Gain** parameter⁵ until the image appears or the screen starts to become white everywhere. See Figure 10-24 for the gain controls.

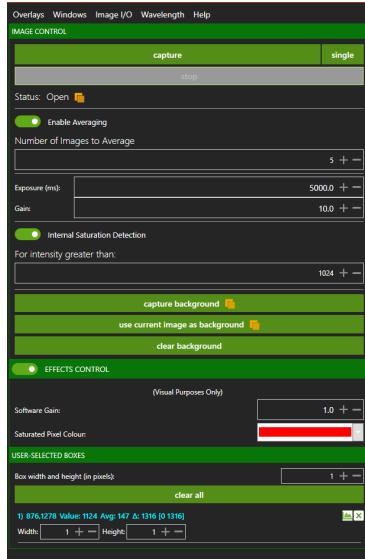


Figure 10-24 A portion of the Camera Window showing the Exposure and Gain controls (set to 5000ms and 10.0 respectively) and the Software Gain control set to 1.0.

At this stage, every attempt should be made to increase the input light signal by increasing the source power, if possible, or by improving the physical coupling of the light into the spectrometer. **Make sure that you use the appropriate fiber; in particular, use a multimode fiber if this is appropriate based on the recommendations of Section 5.** Once these steps have been taken, optimize the displayed signal by varying the exposure and both camera gain and software gain (maximize the exposure, if possible, and minimize the camera gain for best SNR).

The next steps in working with a weak light source are to use the Averaging and Background Subtraction features as described in Section 7. Background Subtraction will enhance a weak signal and reduce the effect of bright or “hot” pixels. Averaging a series of images also enhances the SNR of a weak light source. Details are given in Section 7.

Footnotes

1. For a 10-bit sensor the levels range from 0-1023, for an 8-bit sensor the levels range from 0-255, and for a 14-bit sensor from 0-16,383 levels (i.e. from 0 to $2^n - 1$, where n is the number of bits).
2. This feature can be turned off by switching the EFFECTS CONTROL slider off and on again.
3. For example, for a 12-bit sensor, aim for intensity levels of ~3600-3800.

4. The unwrapped spectrum usually involves averaging over the intensities in several pixels (see Appendix B1). Hence, an intensity of >60-70% of the saturation level in the displayed spectrum may indicate some individual pixels are saturating. It may be wise to return to the camera window and look for saturated pixels. Alternatively, toggle the “Internal Saturation Detection” feature, and any regions of the spectrum that contain saturated pixels will be displayed in red, as shown in Figure 7.2.
5. The Software Gain parameter does not improve the SNR, but merely multiplies the individual pixel levels to give a better visual display of a faint signal.

Section 11 - Glossary

This Section gives a brief description of many of the specialized terms that are used in the spectrometer manuals. If you are uncertain of the meaning of any of the terms in the manuals, check in this section for a definition or description.

Alignment Stripes

See *Stripes*.

Artifact

See *FSR crosstalk*

Background subtraction, Hot pixels

With weak light sources sensor noise can become an issue. Even with no light incident on the sensor (a dark image), it is not uncommon for isolated pixels to record significant levels of illumination. These pixels appear bright or white in the image and are often called hot pixels. One technique for minimizing the effect of hot pixels (and other sources of dark noise) is to record an image with no light (the background image), and then subtract this background image from images taken with the light source. Details of the background subtraction technique are given in Section 7 of this manual.

Blobs

When light from a narrowband source enters the LightMachinery spectrometer, the etalon will only transmit this light at a few fixed angles in the vertical direction. As a result, the camera image consists of a few vertical blobs, each one corresponding to an integral order of the etalon. The positions of these blobs can be used to calibrate the etalon dispersion in the vertical direction. More details, and sample camera images, are given in Appendix C.

Broadband calibration

See *Calibration*.

Blackbody, blackbody radiation

The light from an incandescent lamp has a well-known intensity versus wavelength relationship, characterized by Planck's law - https://en.wikipedia.org/wiki/Planck%27s_law . Hence, this type of light source, often called a blackbody source, can be used to calibrate the intensity axis of LightMachinery spectrometers, as described in Section 6.2

Calibration, Full calibration, Broadband calibration, Etalon calibration,

LightMachinery spectrometers use an etalon to disperse the incoming light in the vertical direction, and a diffraction grating to disperse the light in the horizontal direction. The dispersion in each of these directions must be calibrated before the instrument can unwrap the camera image and display a conventional spectrum of the light source. A broadband source is used to calibrate the diffraction grating dispersion in the horizontal direction, and a narrowband source (of known wavelength) is used to calibrate the etalon dispersion in the vertical direction,

and also calibrate the wavelength scale in the Spectrum window. Full details of the calibration procedures are given in Section 6 of the spectrometer manual.

Camera lens

See *Imaging lens*.

Configuration file

Each LightMachinery spectrometer is shipped with a unique configuration file that can be loaded to the connected PC using the “**Load ...**” command in the software. Once this file is loaded, the spectrometer is configured for the correct wavelength range, etalon thickness, grating groove density etc.

Contrast

A measure of the ability of the spectrometer to detect a weak light source that is very close in wavelength to a much stronger source. Optimizing the instrument contrast is important in applications such as Brillouin or Raman spectroscopy.

Crosstalk, artifacts, spectral artifacts

See *FSR crosstalk*

Dispersion

Diffraction gratings and etalons both separate the incident light into wavelength components by ensuring that different wavelengths emerge at different angles – this variation in angle with wavelength is called dispersion.

Etalon, VIPA

An etalon is a device consisting of two reflecting glass plates and is a key component of LightMachinery spectrometers. The etalon provides dispersion in the vertical direction and is responsible for the high-resolution performance of the spectrometer. Two different types of etalons are used in the various spectrometer models – a conventional Fabry-Perot etalon and a VIPA (Virtually Imaged Phased-Array). The VIPA makes more efficient use of the light from the input source, but otherwise is very similar to a conventional etalon. Further details can be found in Appendix A of this manual.

Etalon Calibration

See *Calibration*.

Factory settings, Factory default settings, Configuration file

See *Configuration file*.

Free Spectral Range, FSR, Orders

The etalon in the LightMachinery spectrometer only transmits light when the wavelength is such that exactly an integer number, N, of wavelengths can fit into an optical round trip between the reflecting glass plates. Successive transmission peaks occur for wavelengths such that (N-1), N, and (N+1) wavelengths fit into the optical round-trip distance. The

separation between these successive transmission peaks is called the Free Spectral Range of the etalon, and the various transmission peaks are often identified as the (N-1), N and (N+1) orders of the etalon. A more detailed description is given in Appendix A of this manual.

FSR

See *Free Spectral Range*.

FSR crosstalk, FCT, crosstalk, artifacts, spectral artifacts

When a strong spectral feature is present in the input light (an intense single-wavelength laser, for example), some of this light may spill over into adjacent stripes on the camera.

When the spectrum is then unwrapped, the light in the adjacent stripe is interpreted as a weak signal at a nearby wavelength. It is important to note that the FCT can only fall precisely n^* FSR away from the real feature where $n = \pm 1, \pm 2, \pm 3$, etc. A full description of crosstalk is given in the Appendix D of this manual.

Hot pixels

See *Background Subtraction*.

Imaging lens, Camera lens

The diffraction grating and etalon in LightMachinery spectrometers disperse the input light into a spread of angles in both the vertical and horizontal directions. The imaging lens focuses these light beams onto the camera sensor and converts the different angles into different positions on the sensor.

Intensity Correction and Envelope Correction, ICE

When this correction is enabled in the software, SpectraLok adjusts the unwrapping process to correct for instrument-related variations of intensity in the vertical axis of the sensor, and variations in the sensitivity of the spectrometer with wavelength. These corrections usually improve the Signal to Noise Ratio of broadband signals.

LSD, Least Squares Deviation

In the Etalon Calibration, the experimental positions of the blobs are compared with the positions predicted by the physical model. The software determines the difference between the experimental and predicted Y-positions of the blob centers, then varies the model parameters to minimize the sum of $(\text{differences})^2$. Finally, the software normalizes the sum of $(\text{differences})^2$ by dividing by the number of blobs and then takes the square root, before reporting the result as the LSD or Least Square Difference (in pixels). A similar procedure is used to determine the LSD in the Grating Calibration. In this case, the comparison is between the experimental and predicted stripe positions in the X-direction.

Look Up Table, LUT

A table created by the SpectraLoK software once all the parameters of the physical model are determined by the calibration process. After a one-time calculation of the LUT, the LUT allows the software to quickly unwrap the spectrum.

LUT

See *Look Up Table*

MMF

Multi-Mode Fiber. This is an optical fiber with a core diameter of 10 microns or greater (often >100um) such that many optical modes can propagate without loss. Generally used for connecting broadband sources to the spectrometer, or for sources with weak light output.

Moire Fringes

If you have a broadband source coupled to a LightMachinery spectrometer, and ring-like patterns are observable when you zoom out of the Camera calibration view, do not be concerned. They are a type of Moire fringe produced by the combination of the actual stripe pattern and the limited resolution of the monitor. More details and examples are provided in the Section 9 of this manual.

Narrowband Source

A light source that consists of a narrow range of wavelengths (ideally, the total spread of wavelengths from the narrowband source should be less than the resolution limit of the spectrometer). The narrowband source is used to calibrate the etalon dispersion in the vertical direction by providing a series of vertical blobs across the camera sensor.

Orders

See *Free Spectral Range*.

Quick Calibration

A calibration procedure used to compensate for any slight drift in the position of the stripes. Fully described in Section 6.

Region of Interest, ROI

The image on the camera sensor contains a great deal of redundant information, particularly in the vertical direction where the spectrum repeats at regular intervals corresponding to the different orders of the etalon. In the horizontal direction, only a selected portion of the wavelength range may be required. The SpectraLoK software allows the user to select a ROI and only unwrap the image information within that ROI.

ROI

See *Region of Interest*.

Resolution

See *Resolving Power*.

Resolving Power, Resolution

If two wavelengths λ , and $\lambda + \Delta\lambda$, can just be separated (or resolved) by a spectrometer, the resolving power of the spectrometer, R , is defined by $R = \lambda/\Delta\lambda$. Hence, a spectrometer operating at 500 nm with $R = 10,000$ can just separate two wavelengths that are spaced by 0.05 nm or 50 pm.

Saturated, Unsaturated, Over-saturated

The camera sensor used in the LightMachinery spectrometer is often a 12-bit device. This means that the light falling on any pixel can take on one of 4095 different levels, depending upon the light intensity illuminating that pixel. Level 0 corresponds to a dark or black pixel. As the intensity of the light falling on the pixel increases, the Level also increases, and the image of the pixel in the Camera Window will change from black to dark grey, to light grey, and finally to white at Level 4095. Any further increase in light intensity will not change the recorded Level beyond 4095. Once the Level reaches 4095, the pixel is saturated.

If there are a significant number of saturated pixels in the image, the spectrum derived from the image may not be accurate. Hence, it is generally recommended that the camera exposure and gain be adjusted to ensure that all individual pixels record levels of less than ~3800 (as observed in the Camera window), corresponding to an unsaturated image. Other sensors may be 8-bit, 10-bit or 14-bit devices, with corresponding different saturation levels (255, 1023, and 16,383 levels).

Single mode, single mode source

See *Narrowband source*.

Single-Wavelength Source

See *Narrowband source*.

Spectral Artifacts

See *FSR crosstalk*.

SpectraLoK

The name given to the software developed at LightMachinery to convert raw sensor images into high-resolution plots of intensity versus wavelength.

SMF

Single Mode Fiber. This is an optical fiber with a small-diameter core (<10 microns) such that typically only one transverse optical mode can propagate without loss. Generally used for connecting lasers or single-wavelength sources to the spectrometer.

Stripes, Alignment Stripes, Stripe Fit

When light from a broadband source (often referred to as “white light”) enters a LightMachinery spectrometer, the diffraction grating disperses this light in the horizontal direction, while the etalon also disperses it in the vertical direction. As a result, the camera image consists of a series of near-vertical bright stripes separated by dark spaces. The positions of these stripes can be used to calibrate the diffraction grating dispersion in the horizontal direction, as described in Section 6.

Stripe Fit

See *Stripes*.

Unwrapping

Light entering a LightMachinery spectrometer is dispersed in both the horizontal and vertical direction before being imaged onto the camera sensor. Once the spectrometer has been calibrated, the relationship between sensor position and wavelength is determined, and the image on the sensor can be unwrapped to allow the intensity versus wavelength spectrum of the light source to be plotted. More details of the unwrapping process are given in Appendix B1.

Unsaturated

See *Saturated*.

VIPA

See *Etalon*.