NEWTEC

Hyperspectral Calibration Board User Guide

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English

Introduction

Accurate calibration is essential for ensuring reliable and repeatable results in hyperspectral pushbroom imaging. The **NEWTEC Calibration Board** is a modular tool designed to streamline the calibration process, enabling precise correction of various imaging parameters.
The calibration board consists of multiple specialized modules, each serving a distinct calibration purpose. These include:

- **White Normalisation** – Ensures consistent reflectance across the entire datacube.
- **Wavelength Extraction** – Provides reference points for accurate spectral alignment.
- **MTF Calculation** – Enables the measurement of the system's spatial resolution across all spectra.
- **Aspect Ratio Correction** – Ensures that pixel dimensions are accurately represented.
- **Grayscale Calibration** – Validates the linearity between optical power and sensor response.
- **Slit Resolution & Focus Module** – Used for achieving optimal focusing of the lens before imaging and to determine the resolution along the entire slit.

By utilizing this board, users can achieve high-precision calibration, improving the accuracy of hyperspectral imaging systems. The modular design allows for flexibility, making it suitable for a range of applications, from research to industrial inspection.
This documentation provides detailed instructions on setup and usage to help you maximize the performance of your hyperspectral system.

Calibration Board and modules:

Specifications:

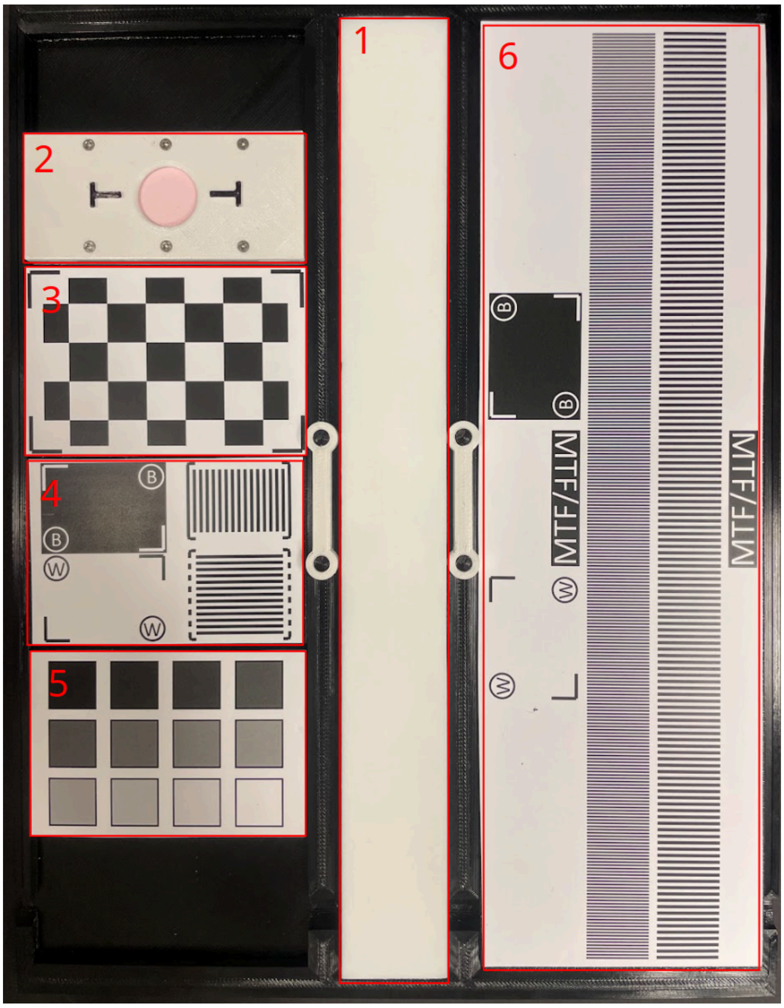
The calibration board is designed with a modular structure to allow flexibility in calibration setups. It measures **32 × 24.5 cm** and features three precision-cut pockets for holding different calibration modules:

- Two pockets measuring **31 × 9 cm** each, designed to accommodate interchangeable 9 cm-wide modules that can be easily inserted, removed, or repositioned.
- One pocket measuring **31 × 3 cm**, specifically designed to hold the white calibration material for reflectance normalisation. This pocket includes a highly reflective aluminum bottom to help with reflectivity.

The calibration board and module bases are 3D-printed in PETG, ensuring durability and stability.
For modules requiring high reflectivity, the top surface is printed using a high-resolution printer on high-reflective synthetic paper, which is both water-resistant and easy to clean.
This modular design allows for customization and reconfiguration to suit different calibration needs, making it a versatile tool for hyperspectral imaging systems.

Current Module Configuration:

Below is an image of the calibration board with its six installed modules marked. This serves as a reference for the next section, where the functionality of each module will be explained in detail.



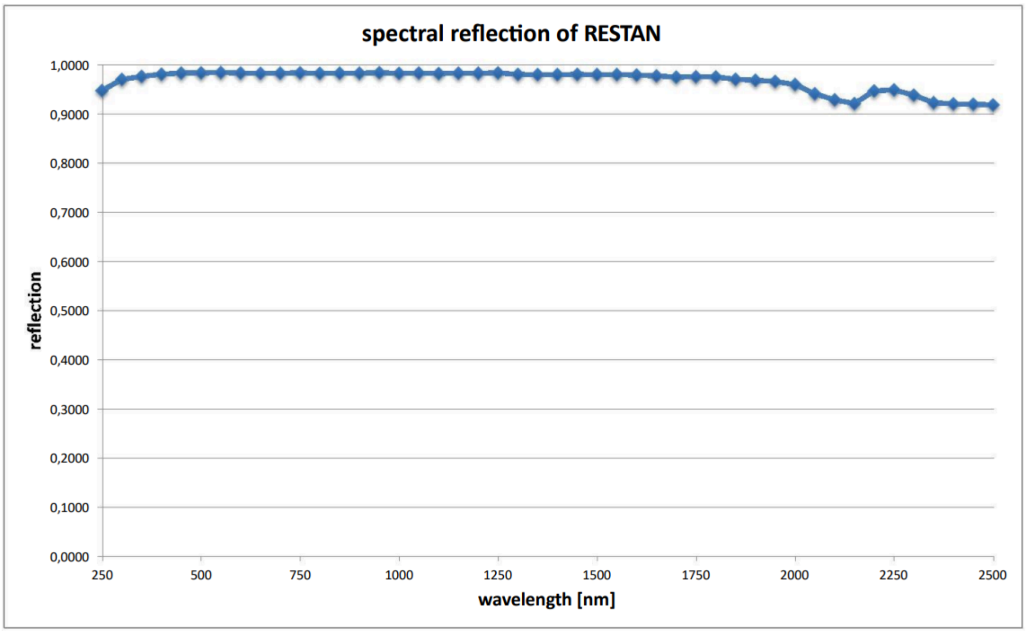
Module Explanation:

1) White Normalisation Module

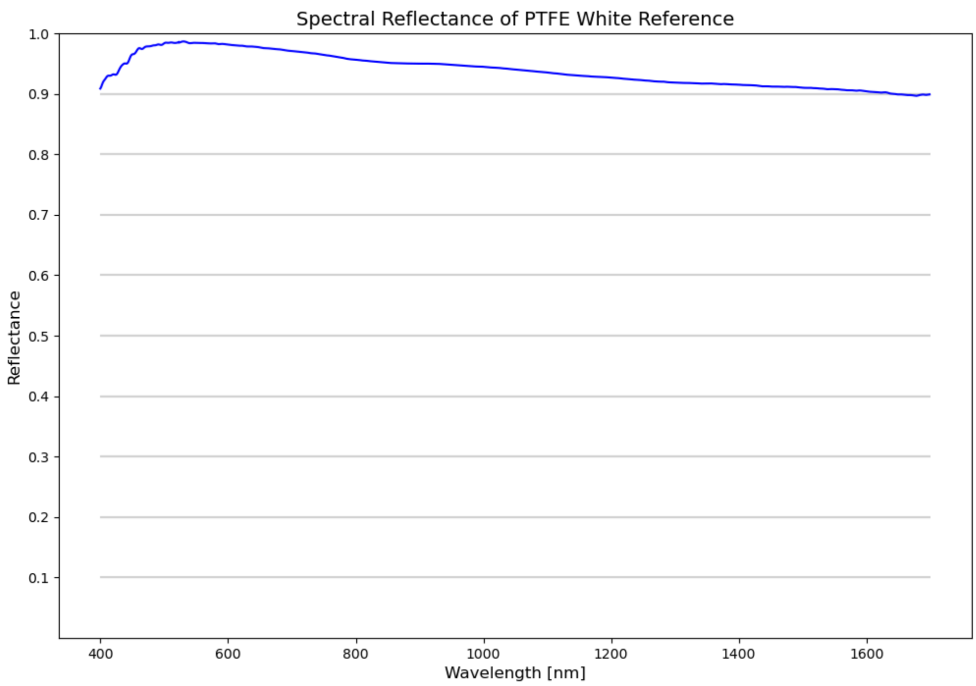
The white reference module is a **31 × 3 cm** high-reflectance material designed to cover the entire field of view of the pushbroom system. Its purpose is to provide a uniform reference for intensity calibration, compensating for variations in illumination and spectral response across the camera's sensor.

The material used in this module can vary depending on the required reflectance accuracy. Several high-reflective standards are available from optical manufacturers. We have included a **PTFE** reference, which provides a fairly good and uniform reflectance in the 400–1700 nm range.

For applications requiring higher accuracy and more stable reflectance, we recommend using Restan, a premium but more expensive material that ensures excellent spectral uniformity. Restan is PTFE based reflectance standard that diffusely reflects more than 98% of light from 400-1700nm. The below graph is taken from the datasheet of the Restan manufacturer (Image Engineering).



For comparison the PTFE reference included with the calibration board exhibits the below reflectance spectrum. We have included the reflectance spectrum of the PTFE reference and the corresponding wavelength axis in the files “PTFE_Reference_Reflectance.txt” and “PTFE_Reference_Wavelength.txt”**.** This can be used to correct the datacube after intensity calibration if a higher precision reflectance cube is needed.



2) Wavelength Extraction Module

The **Wavelength Extraction Module** is designed to utilize the well-defined absorption features of erbium-oxide, a rare earth element with distinct spectral peaks. These absorption features serve as fixed reference points, allowing precise wavelength assignment across the spectral range of the camera.
The module consists of a small container holding an erbium-oxide powder, which exhibits a series of sharp and well-characterized absorption lines. When the hyperspectral system captures an image of this module, these absorption dips appear in the recorded spectrum. Since erbium's spectral response is well-documented, it can be used as a calibration reference.
Instead of assuming a simple linear relationship between spectral channel number and wavelength, we recommend curve fitting as a more precise approach. A high-resolution reference spectrum of erbium, which we provide, should be used to fit the observed absorption features in the measured hyperspectral data. By adjusting the wavelength mapping until the observed peaks align with the reference spectrum, a highly accurate wavelength axis can be derived.

3) Aspect Ratio Correction

The **Aspect Ratio Module** ensures that the spatial dimensions of the hyperspectral images are correctly scaled. It consists of a checkerboard pattern made up of 13 × 13 mm black and white squares.
By measuring the distances between the corners of these squares in both the spatial directions, a ratio can be determined. This ratio allows users to correct differences in spatial axis regardless of the scanning speed chosen and ensures that the aspect ratio of the final hyperspectral image accurately represents real-world proportions.

4) MTF Calculation Module

The **MTF module** is designed to evaluate the spatial resolution of the hyperspectral system by measuring its ability to transfer contrast from object to image. It consists of two sets of black and white line pairs, each with a spatial frequency of 0.49 line pairs per mm:
One set is oriented along the slit and the other along the scanning direction, allowing evaluation of the system's resolution in both spatial dimensions.
In addition to the line pairs, the module includes two black and white reference squares, which serve as intensity baselines for the MTF calculation. By comparing the measured contrast between the peaks (white lines) and valleys (black lines) to these reference points, the system's ability to reproduce fine spatial details can be quantified.

5) Grayscale Calibration

The **grayscale calibration module** is designed to assess the linearity of the camera's response to different intensity levels. It consists of 12 squares, each measuring 15 × 15 mm, printed in differing grayscale levels ranging from white (1.0 reflectance) to black (0.0 reflectance).
By capturing the hyperspectral response from each square and comparing it to the known reference values, users can evaluate how accurately the sensor records intensity variations. This allows for linearity correction, ensuring that the measured signal corresponds proportionally to the actual optical power.

6) Slit Resolution & Focus Module

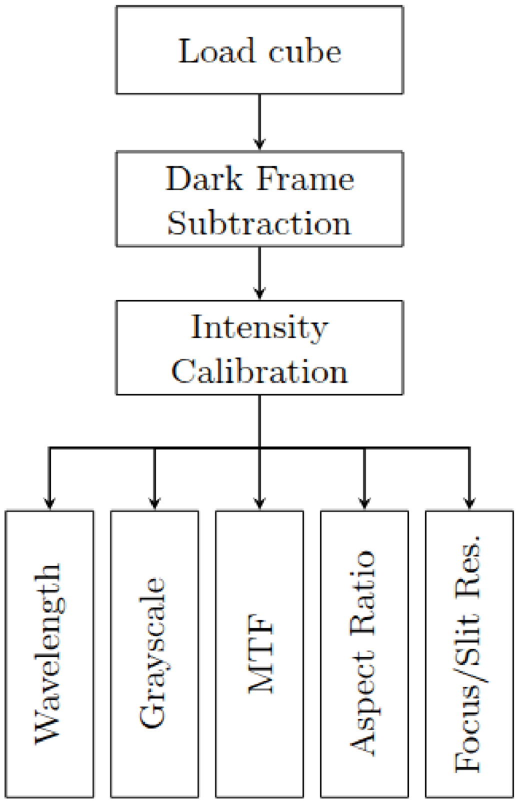
The **slit resolution and focus module** is designed to evaluate resolution uniformity across the slit and assist in precise focusing of the imaging system. This large module spans the entire field of view of the slit. It contains:

- Two sets of black and white line pairs with spatial frequencies of 0.49 and 0.98 line pairs per mm, allowing for detection of resolution variations along the slit.
- Black and white reference squares, serving as intensity baselines for contrast measurements.

To ensure optimal focus, users can align the slit with the black and white lines while using the live camera feed. By adjusting the lens focus until the lines appear sharp across the entire slit, the system achieves maximum image sharpness before scanning.

Suggested Method of Calibration:

In the following section, detailed instructions on the use of each module will be provided. The optimal order of operations is outlined in the calibration pipeline diagram below. Following this workflow ensures that the resulting data is reproducible, easier to interpret, and more comparable to other datasets, as it generates the closest approximation to a true reflectance cube that can be achieved with a given setup.



0) Dark Frame Subtraction

The first step in the calibration process is to subtract a dark reference from every image acquired by the system. This is necessary to remove unwanted dark current noise and thermal noise, both of which can introduce errors in intensity measurements. This is especially important for measurements with important information in lower signal areas of the datacube.

To obtain and use a dark reference:

1. Cover the lens completely to prevent any light from entering.

2. Capture a dark reference datacube $\boldsymbol{D}(x, y, \lambda)$, ensuring the same exposure time and settings as used for the rest of the data.
3. Store this image as the dark reference and use it to do a pixelwise subtraction from all subsequent images:

$$\mathbf{I}_{Corrected}(x, y, \lambda) = \mathbf{I}(x, y, \lambda) - \mathbf{D}(x, y, \lambda)$$

where:

- $\mathbf{I}(x, y, \lambda)$ is a given hyperspectral datacube captured using the same settings as the dark reference.
- $\mathbf{D}(x, y, \lambda)$ is the dark reference.
- $\mathbf{I}_{Corrected}(x, y, \lambda)$ is the resulting corrected datacube.

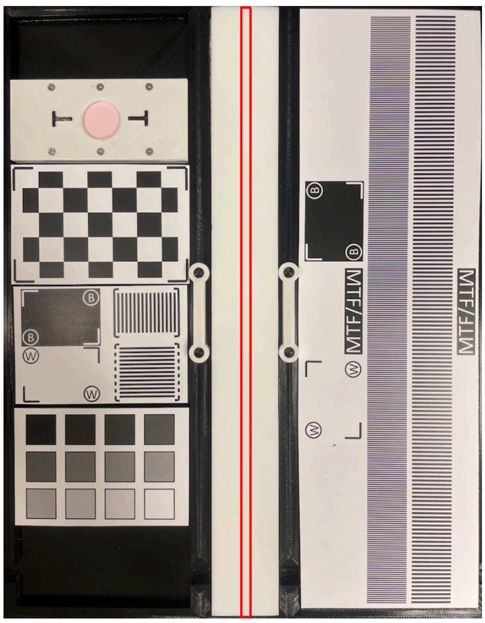
1) Intensity Calibration (White Normalisation)

Normalisation with respect to a white reference is an essential preprocessing step in hyperspectral imaging. Several factors in the setup introduce unwanted variation in the hyperspectral datacube. Variations in the illumination along the slit, non-uniform spectral response of the camera and wavelength dependent lighting intensities can all be corrected for by doing a pixelwise division with a white reference.
By using a highly reflective white reference material, we establish a physically meaningful reference point, allowing all subsequent data to be expressed relative to this reference. This ensures that the hyperspectral data can more accurately be expressed in terms of relative reflectance, making it more consistent and easily comparable to other empirical data.

How to Perform White Calibration:

1. **Perform Hyperspectral Scan on Calibration board**
   Capture a hyperspectral datacube that includes the white reference material covering the field of view in the direction of the slit.

2. **Select Appropriate Region of Interest**
   Select the region of the datacube corresponding to the center of the white reference material as shown to the right. Selecting the innermost 20-30 pixels ensures the best result as the edges of the material are influenced by the diffusion length of the light. Doing this results in a smaller 3D cube that contains only the white reference. $\mathbf{I}_{White}(x, y, \lambda)$



3. **Generate Mean White Reference Matrix**
   Average the selected region row-wise, producing a mean white matrix $\boldsymbol{W}(y, \lambda)$, where each spectral channel has an averaged reference value for each row of the original image.

$$\mathbf{W}(y, \lambda) = \frac{1}{N} \sum_{i=1}^{N} \mathbf{I}_{White}(x_i, y, \lambda)$$

4. **Perform White Normalisation of Data**
   Perform pixel-wise normalisation by dividing each pixel in a given datacube (captured under equal conditions) by the corresponding value in the mean white matrix:

$$\mathbf{I}_{Normalised}(x, y, \lambda) = \frac{\mathbf{I}(x, y, \lambda)}{\mathbf{W}(y, \lambda)}$$

where:

- $\mathbf{I}(x, y, \lambda)$ is a given hyperspectral datacube captured under the same conditions as the white reference.
- $\mathbf{W}(y, \lambda)$ is the mean white reference matrix.
- $\mathbf{I}_{normalised}(x, y, \lambda)$ is the resulting white-normalised datacube.

(Remember to do a **Dark Frame Subtraction** of all the hyperspectral data, including the white reference before doing the white normalisation step.)

2) Wavelength Extraction

The wavelength extraction module enables precise mapping of spectral channels to physical wavelengths, ensuring that hyperspectral data is accurately referenced. While the wavelength axis remains nearly constant for each camera, minor variations may occur between different cameras due to manufacturing tolerances and optical alignment differences. Additionally, even within the same camera, the wavelength axis may drift slightly over time due to thermal expansion, mechanical stress and environmental factors such as vibrations or humidity changes.

How to Use the Wavelength Extraction Module

To perform wavelength calibration, a white-normalised hyperspectral datacube that includes the wavelength extraction module is required. This module contains erbium-oxide powder, which has a well-defined reflection spectrum characterized by sharp absorption peaks distributed across the 400–1700 nm range.

1. **Select the Region of Interest**
   Identify and extract the region in the hyperspectral datacube where the erbium oxide powder is visible.

2. **Generate a Mean Erbium Spectrum**
   Average the extracted region over the spatial dimension, resulting in a mean erbium oxide spectrum. This smooths out noise and provides a clearer spectral signature.

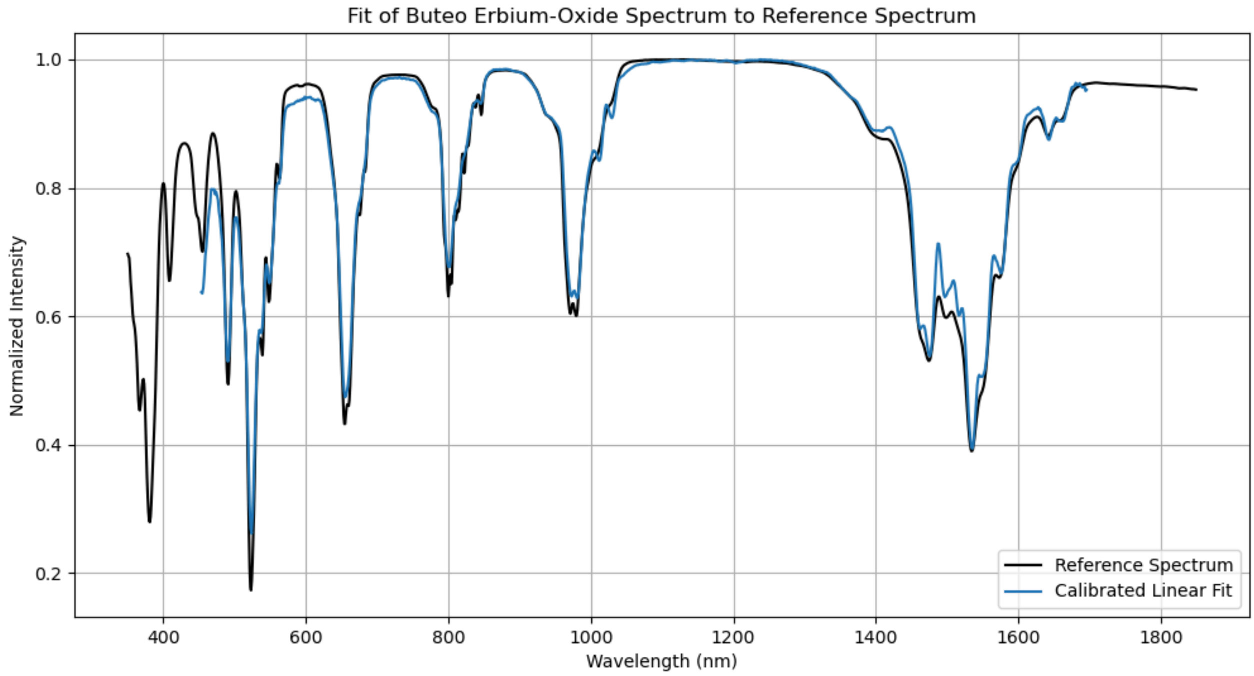
3. **Compare with a Reference Spectrum**
   Along with the documentation a reference erbium oxide spectrum is provided, which serves as a reliable standard for wavelength alignment. This reference along with the corresponding wavelength axis can be found in the files “**ErbiumOxide_spectra.txt**” and “**ErbiumOxide_wavelength.txt**”

4. **Curve Fitting for Accurate Calibration**
   While performing a simple linear fit using the absorption peak positions in most cases will work fine, we recommend using a curve-fitting algorithm to increase the accuracy of the fit. The wavelength axis is nearly linear, slight deviations can however reduce accuracy if a linear approximation is used. Using a second order polynomial curve fitting accounts for these deviations, ensuring a more precise mapping of spectral channels to physical wavelengths.

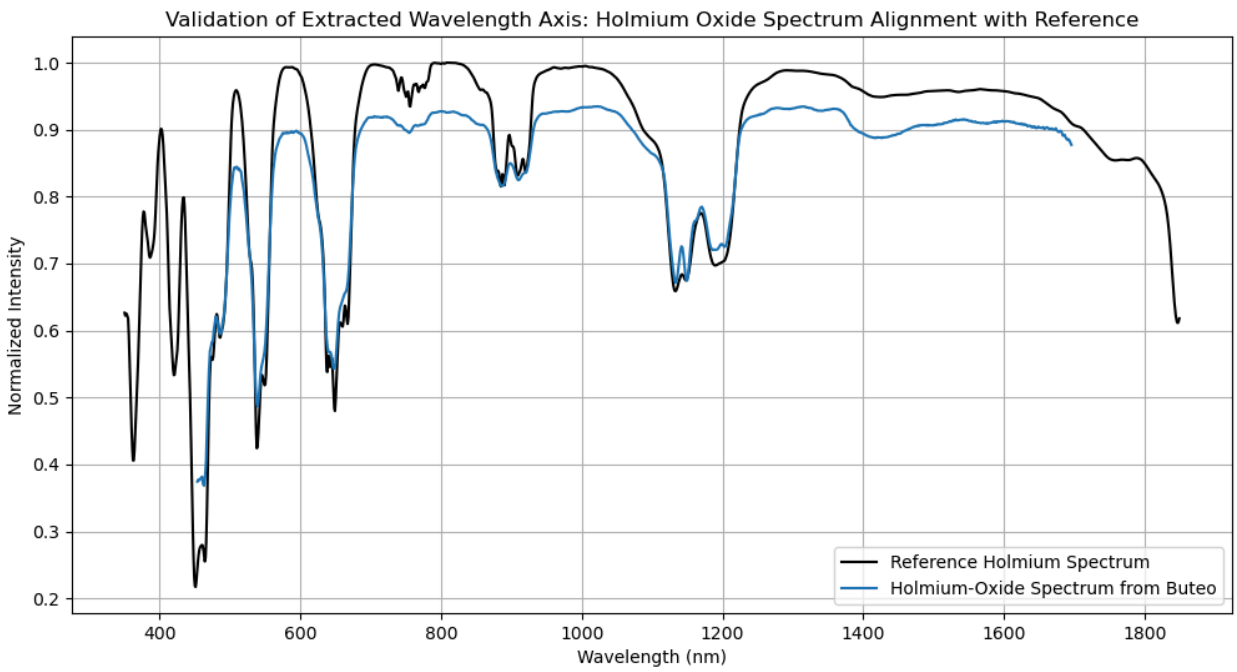
Applying the above method produces the below figure displaying a linear curve fit applied to the erbium oxide spectrum extracted from a hyperspectral image captured with the Buteo. This extracted spectrum is matched to a known reference spectrum, allowing for precise mapping of channel # to physical wavelength as:

$$\lambda = 1.382x + 453.2$$

with λ and x being wavelength in nm and spectral channel number respectively. Note that the crop-top setting will influence the relationship between channels and physical wavelength. A new spectral axis should therefore be generated if crop-top settings are changed.



Additionally, a holmium oxide spectrum from the same hyperspectral image is extracted. The below figure shows the holmium-oxide spectrum placed alongside a reference spectrum of holmium oxide. By applying the wavelength axis obtained from the erbium-oxide calibration to the holmium data, it is evident that the measured holmium spectrum aligns perfectly with the reference, confirming the accuracy of the wavelength axis derived using the curve-fitting algorithm.



3) Aspect Ratio Module

The aspect ratio calibration module ensures that the spatial scaling of the hyperspectral data is accurate regardless of the scanning speed. While this correction may be ignored in many instances, correct geometric proportions is crucial in several applications.

How to Use the Aspect Ratio Calibration Module:

1. **Select the Region of Interest**
   Extract the section of the hyperspectral datacube containing the checkerboard pattern from the calibration board.

2. **Detect the Checkerboard Corners**
   Locate the coordinates of the tile corners. If using python this can be done using OpenCV's **findChessboardCorners()** function accurately locating the tile corners at a sub-pixel level.

3. **Calculate the Aspect Ratio Correction Factor**
   Compute the average distance between adjacent corners along both spatial directions (along the slit and along the conveyor belt). Compute the correction factor as the ratio between these two distances:

4. **Resize the Datacube**
   Apply the correction factor to the datacube using OpenCV's **cv2.resize()** function, or similar, to interpolate and rescale the data, ensuring the spatial dimensions are correctly proportioned.

4) MTF Module

The MTF module quantifies the spatial resolution of the hyperspectral imaging system in both spatial dimensions as these are independent of each other. This is done by measuring the system's ability to accurately reproduce high-contrast black and white line pairs at a known spatial frequency.

How to Use the MTF Module:

1. **Extract the Line Pair Regions**
   Select the two regions in the hyperspectral datacube that contain the black and white line pairs, one aligned along the slit and the other along the scan direction.

2. **Compute the Average Line Pair Signal**
   For each spectral channel, average the signal along the spatial dimension of the line pair pattern.
   This creates an oscillating signal corresponding to the alternating black and white lines.

3. **Extract Peak and Valley Values**
   Identify the peaks (white lines) and valleys (black lines) of the oscillating signal for each spectral channel.
   Compute the average peak and valley values separately for each spectral channel.

4. **Compute the Black and White Reference Values**
   Extract the mean intensity values from the solid black and white reference squares for each spectral channel.

5. **Calculate the MTF**
   The MTF value for each spectral channel is given by dividing the difference between average white peak and black valley values with the difference between white and black reference values as:

$$MTF(\boldsymbol{\lambda}) = \frac{\boldsymbol{I}_{peak}(\lambda) - \boldsymbol{I}_{valley}(\lambda)}{\boldsymbol{I}_{white.ref}(\lambda) - \boldsymbol{I}_{black.ref}(\lambda)}$$

   This expresses the system’s ability to transfer contrast at the given line pair frequency for each wavelength (0.49 lp/mm in this case).
   By analyzing the MTF values across wavelengths, one can assess how well the camera maintains resolution across the entire spectral range.

5) Grayscale Module

The grayscale calibration module is designed to assess and correct potential nonlinearities in the relationship between sensor output and optical power. It contains 12 printed squares, each with a known grayscale value ranging from white to black. By comparing the sensor's measured response to these known reference values, one can evaluate the system's optical response and apply corrections if needed.
The grayscale included with the calibration board is a simple approximation of a grayscale created by printing and gamma-correcting a computer generated grayscale on a piece of high quality paper. While this provides a useful approximation of the system's response, it is by no means a perfect radiometric standard. For applications requiring precise mapping between optical power and sensor output, we recommend using a calibrated grayscale target from providers such as Labsphere.
For the Buteo system the sensor response is approximately linear, and any observed deviations are likely due to imperfections in the printed grayscale. Other systems may exhibit stronger nonlinearities, which can also vary across the spectral range. In such cases, correction should be applied before comparing the data to linearly calibrated datasets.

How to Use the Grayscale Module:

1. **Compute Mean Reflectance of Each Square**
   Select each of the 12 grayscale squares and calculate the mean reflectance value within each square. This can be done for each spectral channel individually if wanted.

2. **Compare with Reference**
   Compare the measured values to the known reference values provided in "**Grayscale_Reference_Values.txt**"

3. **Fit correction Function**
   If the output deviates significantly from linear, fit a smooth function (e.g., polynomial or spline) to the relationship between measured and reference grayscale values.

4. **Apply the fitted function as a pixel-wise correction**
   Use each pixel's value as input to the function to generate a corrected and linearised output. This can be done for each spectral channel to ensure accuracy across the range.

6) Slit Resolution & Focus Module

The slit resolution and focus module serves two primary purposes.

1. **Optimizing Lens Focusing**
2. **Evaluating Resolution Uniformity Along the Slit**

Using the Module for Focus Adjustment:

1. Place the black and white line grating on the conveyor belt within the camera's field of view.
2. Look at the camera's live feed and adjust the lens until the lines appear sharp and are clearly visible in the whole field of view.
3. Once the lines are clearly visible fine adjustment can be made using the **Image Variance** counter next to the live feed. Once Image variance is maximized the lens is optimally focused and data can be collected.

Measuring Resolution Variation Across the Camera's Field of View

1. **Extract the Line Pair Regions**
   Select the two regions in the hyperspectral datacube that contain the black and white line pairs with differing spatial frequencies.

2. **Compute the Average Line Pair Signal**
   For each spectral channel, average the signal along the spatial dimension of the line pair pattern.

This creates an oscillating signal for each spectral channel corresponding to the alternating black and white lines.

3. **Compute White Peak and Black Valley Curves**
   Extract the values of white peaks and black valleys of the oscillating signal. Interpolate these values to create two curves along the camera's field of view. One for black valley intensities and one for white peak intensities.

4. **Compute the Black and White Reference Values**
   Extract the mean intensity values from the solid black and white reference squares for each spectral channel.

5. **Compute a Local MTF Curve**
   Curves can now be created displaying the local MTF values for each spatial frequency across the camera's field of view. By subtracting the curves made from white peaks and black valleys and dividing the curve with the difference between white and black reference squares the local MTF curve is computed.

$$MTF_{curve}(x, \lambda) = \frac{\mathbf{I}_{peak}(x, \lambda) - \mathbf{I}_{valley}(x, \lambda)}{\mathbf{I}_{white.ref}(\lambda) - \mathbf{I}_{black.ref}(\lambda)}$$

This results in an MTF profile across the field of view, showing potential drops or inconsistencies in resolution at different spatial positions.

Final Notes

Following this guide will ensure the optimal use of the calibration board and its modules. Following the suggested workflow results in optimal hyperspectral data that is consistent and comparable with data acquired from different setups.
It’s worth noting that while the included modules are designed to be practical and affordable, they aren’t perfect. Both the grayscale and white reference can be easily upgraded for high quality reflectance standards if a given application demands high precision reflectance data. High end standards can be purchased from companies such as **Image Engineering** or **LabSphere**.
Still, even with the default setup, following the workflow will get you close to true reflectance data and optimize the systems performance giving a great baseline for any meaningful analysis.

While all calibration steps currently are done manually we are actively working on automating the entire calibration process, allowing users to simply scan the board and complete all calibration steps with a single click. Internal testing of this automation workflow has already begun, and we will notify you as soon as the software becomes available to our customers. Once released, all relevant documentation and updates will be accessible through Qtec’s website.