Spectral Radiance Analysis Software

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Spectral Radiance Analysis Software

1.0 INTRODUCTION

The Spectral Radiance Analysis Toolkit (SRAnal) code provides the basic capability for data calibration, spectral correlation, image manipulation and display of the data collected by the SOC 710 hyperspectral imager system. This document provides a User's Guide to the functionality of this code as well as an overview to the spectral processing techniques used.

The SRAnal code is a PC/Mac/Linux software package that provides a basic tool kit for performing spectral correlation analysis on hyperspectral image cubes. The code is written in Java and will run on any computer or workstation that has the Java Virtual Machine (JVM) 1.6 or higher installed. The SRAnal standard installation for Intel/Windows based platforms automatically sets up the run time environment and executable program. JVMs for other platforms are available for download from www.sun.com. Figure 1 shows the User Interface (UI) for the SRAnal code.

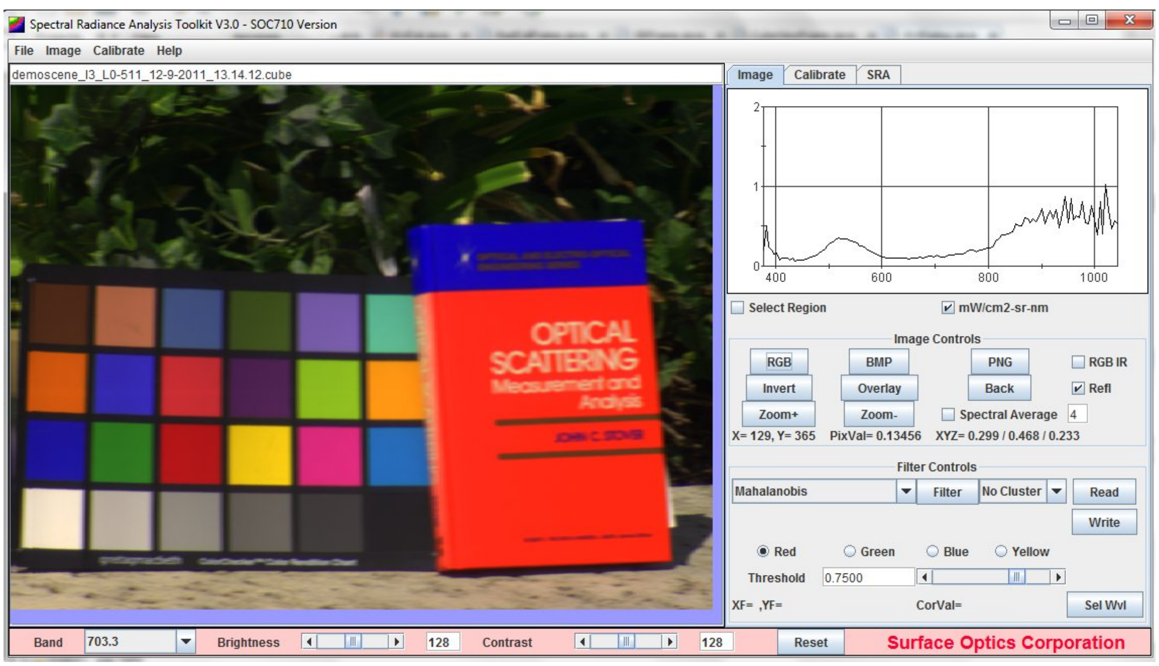

Figure 1: SRAnal User Interface.

The SRAnal interface has three tabs for loading, calibrating and processing hyperspectral image cubes and two display panels for viewing images and spectral plots. The menu functions and the functions of the controls are described below. Many of the functions are available as both menu selections as well as buttons on the Tab panels.

2.0 FILE MENU

The *File* menu, shown in Figure 2, loads and saves image cubes and also allows the user to save float formatted calibrated cubes and sub-cubes for input into other applications (e.g., ENVI, MATLAB). The *Quit* button exits the application.

Figure 2: The File Menu.

2.1 Open and Save Menu

The *Open* button opens a file selection dialog box for selecting a hyperspectral image cube. The code reads Band Interleaved by Line (BIL) format (line 1, band 1; line 1, band 2; … etc) image cubes that are produced from the raw data stream saved from the SOC-710 sensor system. The cubes are 696 by 520 pixels by 128 bands, stored as 16 bit integers plus a 32768-byte header for a total image size of 92.8 Mbytes. Image cubes are typically saved with a ".cube" or ".cub" extension, but this is not a requirement of the software.

The *Save* button opens a dialog box for saving and/or renaming modified image cubes after calibration or re-calibration.

2.2 Save Float and Define Float Sub Cube Menu

The image cubes are saved as 16 bit shorts, with the calibration information stored in the header or footer of the file. For accessing the image cube data from other applications the *Save Float* and *Save Band Image* options are available. *Save Float* saves the data as calibrated, 32 bit floating point numbers with a 32768 byte header in BIL format. These image cubes cannot be re-calibrated.

The user can also save sub-cubes in float format using the *Define Float Sub Cube* menu item, which opens up the dialog box shown in Figure 3. The user can select the start/stop row and column of the sub image as well as the number of beginning and ending spectral bands to skip. The band selection also accounts for the spectral band averaging option, which is described below. The float and sub cube images can also be read and processed by SRAnal, but they cannot be re-calibrated.

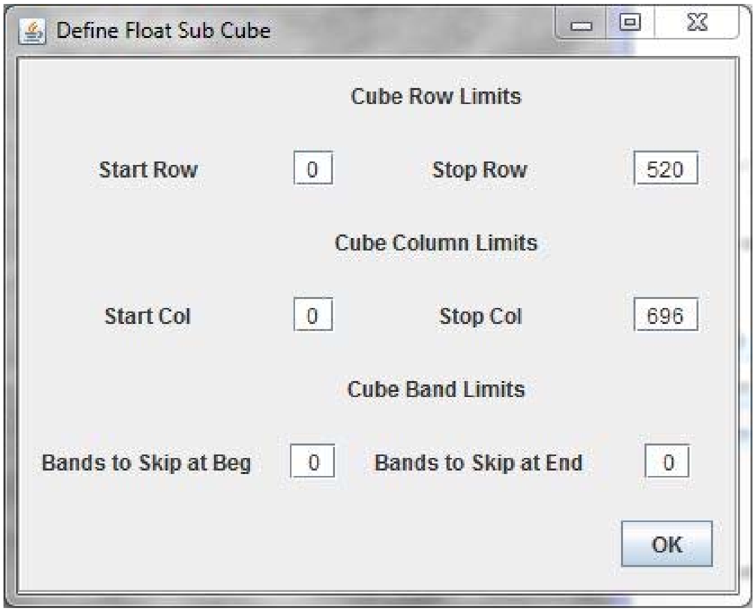

Figure 3: Define Float Sub Cube Dialogue Box.

2.3 Save Band Image Menu

The *Save Band Image* menu item allows the user to save a particular image plane (selected using the *Band* combo box described below) as a file of space separated (x,y) pixel values in text format. There is a one line header with the original cube file name and the wavelength. The pixel values are in the selected units of the display (counts, radiance or reflectance).

3.0 IMAGE DISPLAY PANEL

The *Image Display Panel*, Figure 4, displays individual gray scale image planes from the spectral cube as well as RGB integrated images, correlation image results and correlation overlay images generated by SRAnalysis. Brightness and contrast for the display can be adjusted using the Brightness/Contrasts Controls located at the bottom of the image window. A wavelength selection combo box is also located at the bottom of the window that allows stepping through the individual bands of the cube displaying the corresponding gray scale image as seen by the sensor.

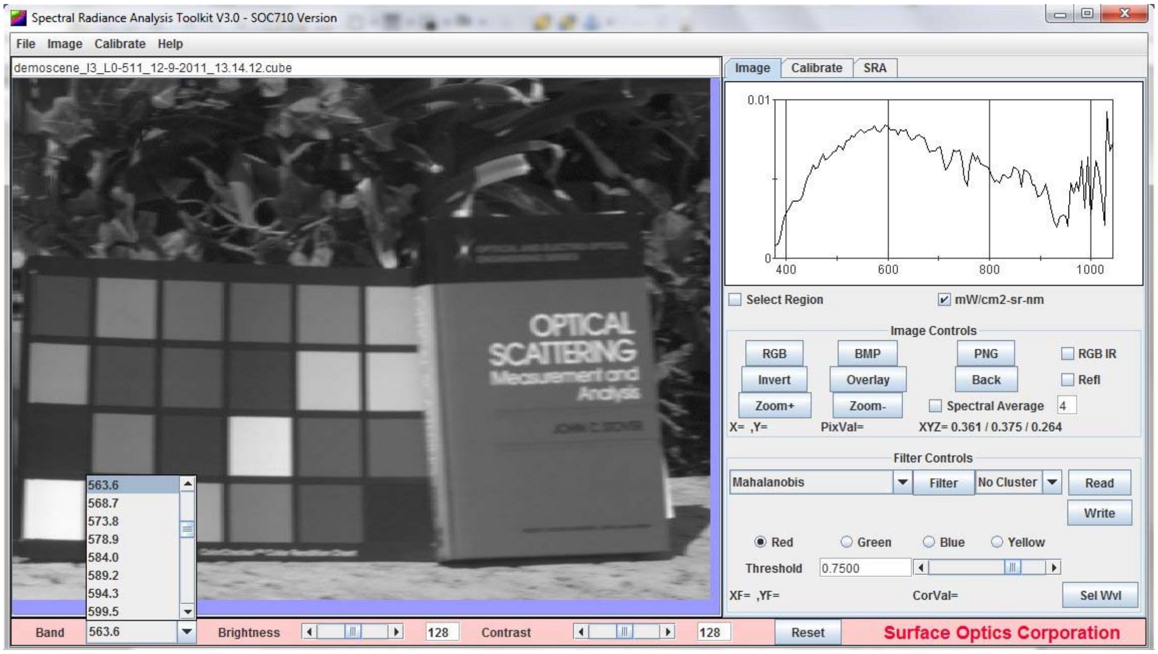

Figure 4: The Image Display Panel.

3.1 Spectral Display

The spectral plot in the upper right corner of the window, and shown in Figure 5, displays the full spectrum for the pixel pointed to in the image display. The units are either counts, radiance or reflectance depending on the calibration option selected, which is described below.

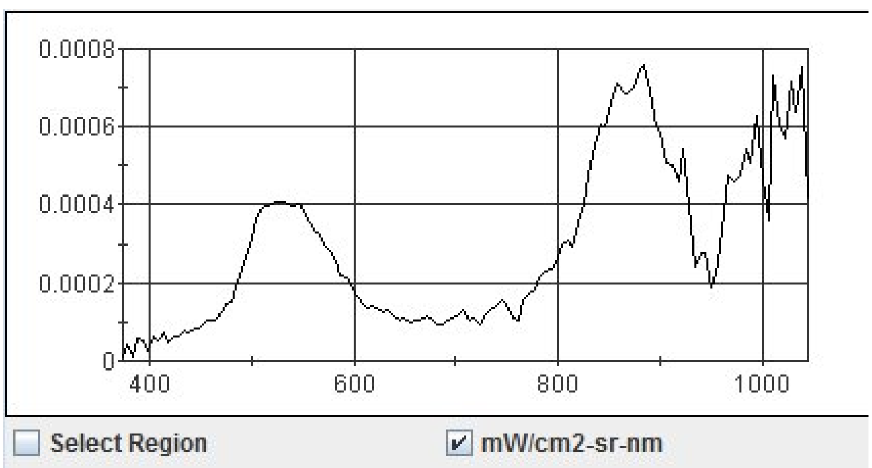

Figure 5: Spectral Display.

The *mW/cm2-sr-nm* check box toggles between radiometric units and integer counts if the data is calibrated. Note: In order to display calibrated radiances or reflectances, the user must first perform a calibration of the data cube as outlined in the calibration section of this manual. If a calibration has not yet been performed on the data, then the radiance checkbox will be disabled.

The *Select Region* check box allows the user to select a region of pixels to be spectrally averaged, or to outline a target region. This process will be described below.

3.2 Brightness/Contrast Controls

Two scroll bars, shown in Figure 6 below, control the brightness/contrast of the displayed image. The *Reset* button resets the brightness/contrast values to the original setting.

Figure 6: The Brightness/Contrast Panel.

4.0 IMAGE CONTROLS BOX AND IMAGE MENU

The *Image Controls Box*, shown in Figure 7, provide controls for generating color images, modifying the display and overlaying results and also for saving the displayed image. These functions are also available from the *Image Menu*. The status line along the bottom of the box provides information on the pixel pointed to in the image display: (x,y) position, the pixel value in the selected units (counts, radiance or reflectance), and the XYZ color coordinates of the pixel, described below, computed using the tri-stimulus response function and a selected standard illuminant.

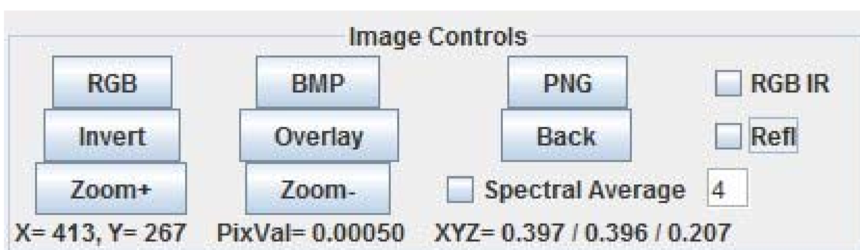

Figure 7: Image Control Box.

The basic XYZ calculation is based on the integral of the spectral radiance with the tri-stimulus values. In reflectance mode, the spectral irradiance illuminating the scene has been normalized out. Using the *Illuminant* menu item, located under the *Calibrate Menu* and shown in Figure 8, the user can select a standard spectral illumination definition for the calculation. The calculation is specified in ASTM paper 308.

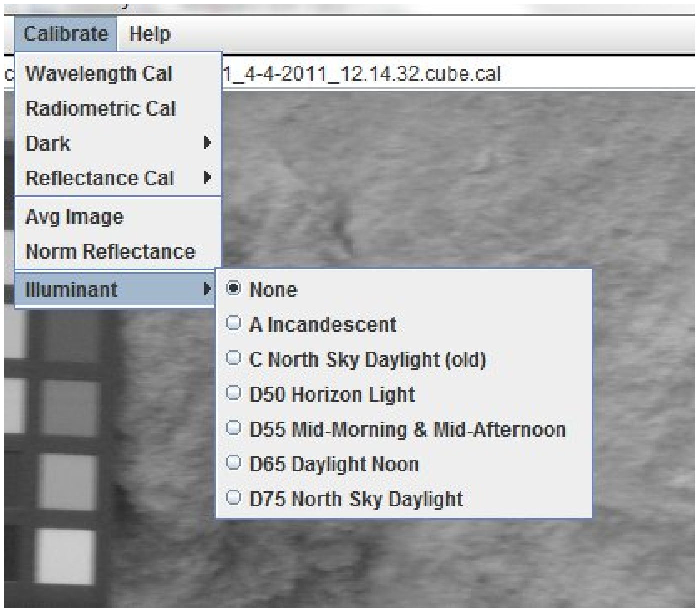

Figure 8: Selection of Standard Spectral Irradiance for XYZ Calculation.

4.1 Reducing the Number of Bands: *Spectral Average*

The user can reduce the number of bands in the image cube using the *Spectral Average* check box and adjacent text box. Checking the box will sequentially average N bands, where N is the number in the adjacent text box. All spectral filters will need to be reselected, or re-read in from a file. This is done on the fly, and can be reversed by unchecking the box. To save the reduced resolution image cube for subsequent processing, use the *Save Float* option, but this action cannot be reversed.

4.2 Generating and Saving Color Images

Pressing the *RGB* button produces a color image from the data by integrating the spectra for each pixel with the tri-stimulus response functions to produce X, Y Z color values which are assigned to the RGB channels of the image display, shown in Figure 9.

The *RGB IR* check box provides an alternate RGB model, shown in Figure 10, which emphasizes the NIR bands (700 to 900 nm). This is useful in agricultural applications where the user wants to focus on the longer, non-visible wavelengths in the image. In this case, the red channel is replaced by the NIR bands, the green channel is replaced by the usual tri-stimulus red calculation, and the blue channel is replaced by the tri-stimulus green calculation. The data in the blue end of the spectrum is ignored for this option.

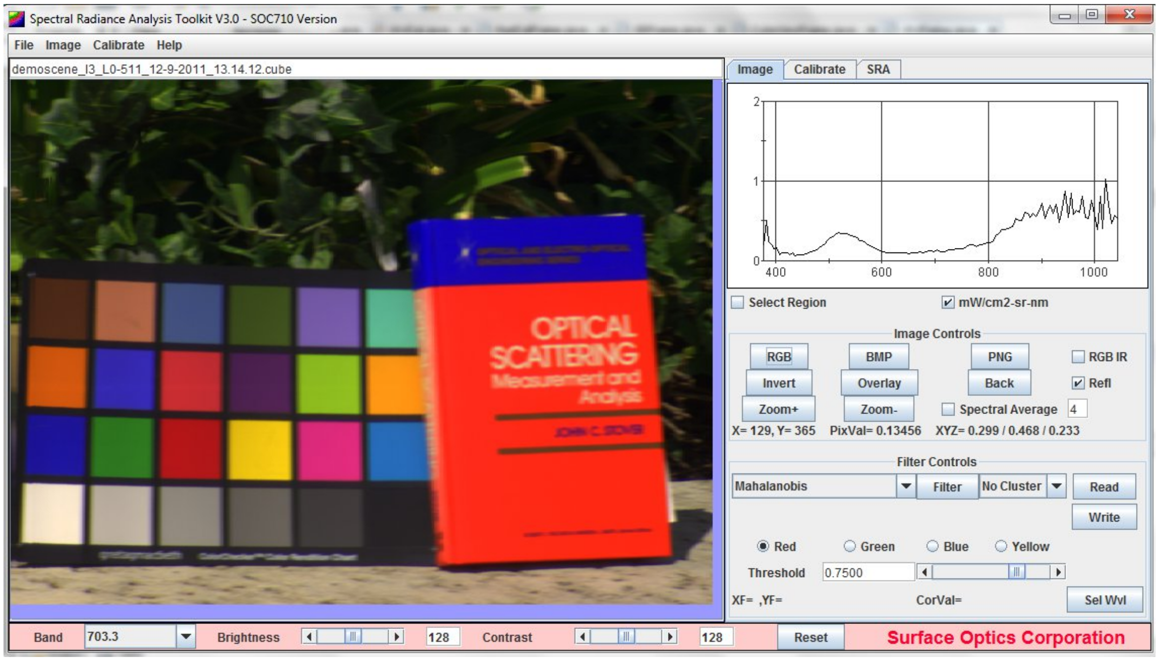

Figure 9: RGB Image Display.

The image in Figure 10 shows live vegetation as well as a wreath of artificial leaves, which is obvious in the RGB IR image because the fake leaves do not exhibit the high NIR reflectance due to chlorophyll, which is seen in the live plants.

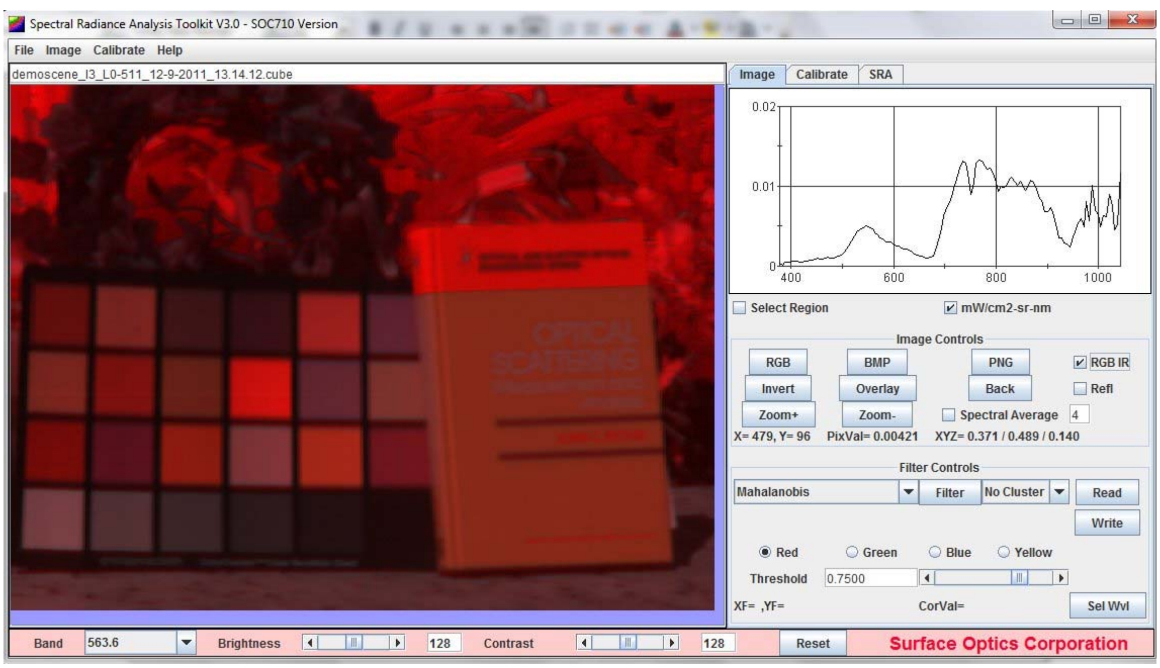

Figure 10: *RGB IR* Image Display.

4.3 Changing the Display: the *Overlay, Invert* and *Back* Buttons

The *Overlay* button overlays the current correlation map result with the current image display (gray scale or RGB) and displays the result in the image display window. Results of multiple correlation operations can be overlaid on the same image, in effect displaying the effect of OR'ing the results of multiple correlation operations, this will be described in the spectral filtering section below.

The *Invert* button toggles the display between an inverted scale and the original scaling. Figures 9 and 11 show a color image and its corresponding inverted image.

The *Back* button returns the display to the original image after an *Overlay* operation.

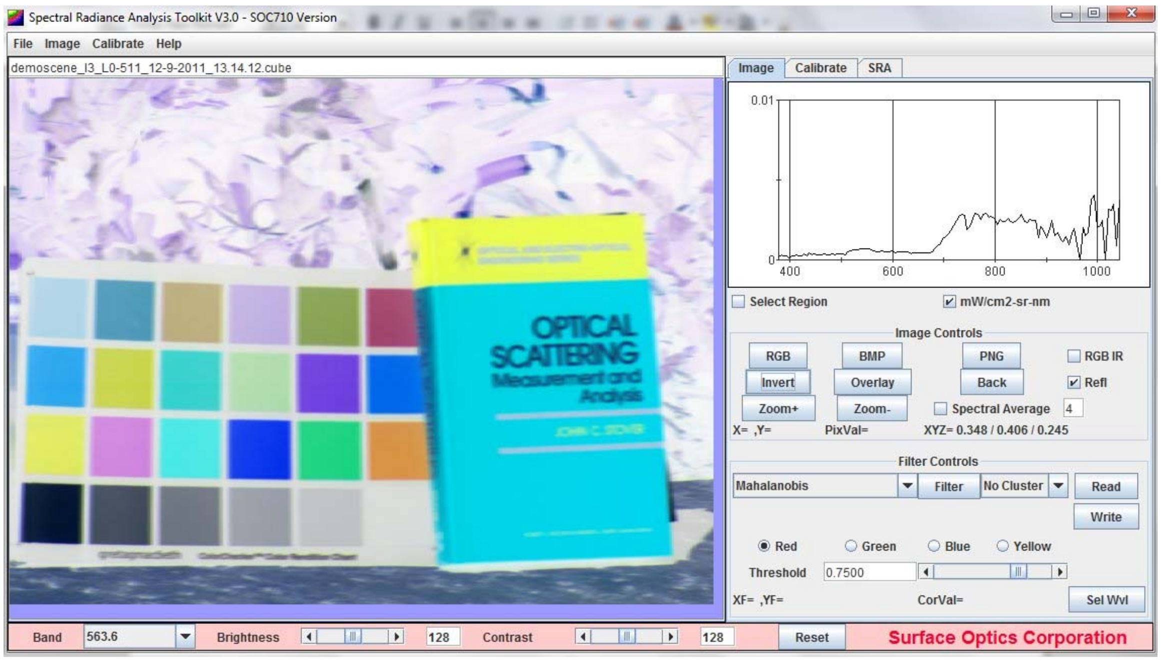

Figure 11: Inverted Color Image Display.

4.4 Saving the Image : the *PNG* and *BMP* Buttons

The *BMP/PNG* buttons produces a Windows bitmap (.bmp) or Portable Network Graphics (.png) image file of the current image in the display window, including the results of any filtering and overlay operations. The image file is written to the same directory, and has the same name as the image cube with the extension ".bmp." or ".png". <u>Note: this operation will automatically overwrite image files with the same name. If the user wants to generate multiple result images from the same image cube, the image file should be manually renamed after each operation</u>.

4.5 Spatial-Spectral Images: the *Cube View* Menu Item

Other views of the image cube are also useful for providing insight into the spectral data. This is provided through the *Cube View* Menu Item, found under the *Image* Menu. This brings up the *Cube View* window which provides a Column-Band or Row-Band Image, shown in Figures 12 and 13, and which can be toggled using the Combo Box.

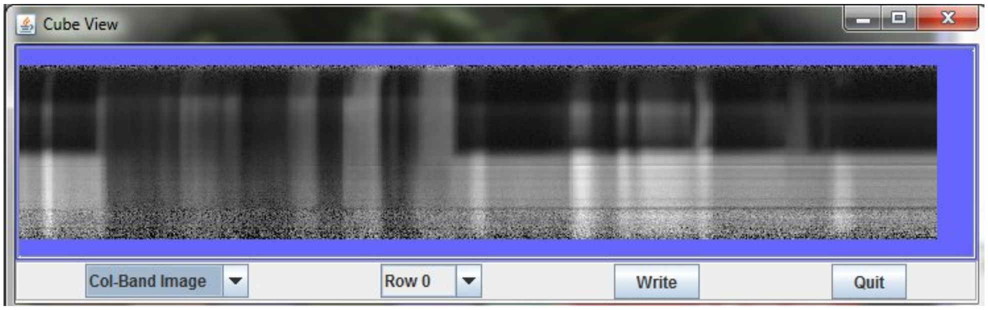

Figure 12: Cube View: Column-Band Image.

The row or column displayed is selected with the *Row/Column* Combo Box. Also, a 2D text file of the Row/Col selected image is saved using the *Write* button with the original file name with the type/location appended to the name.

Notice the phenomenology that can be observed in the spatial-spectral images. In Figure 12, the Row 0 image is comprised of vegetation (see Figure 9). The Column-Band image clearly shows the chlorophyll region (> ~700 nm) as the white band across the bottom of the image. This is clearly missing in the portion of the image comprising of the artificial plants. Also notice the bright stripe in the dark region of the image; this is the green (~550 nm) reflectance peak, which is also spectrally shifted for the artificial leaves.

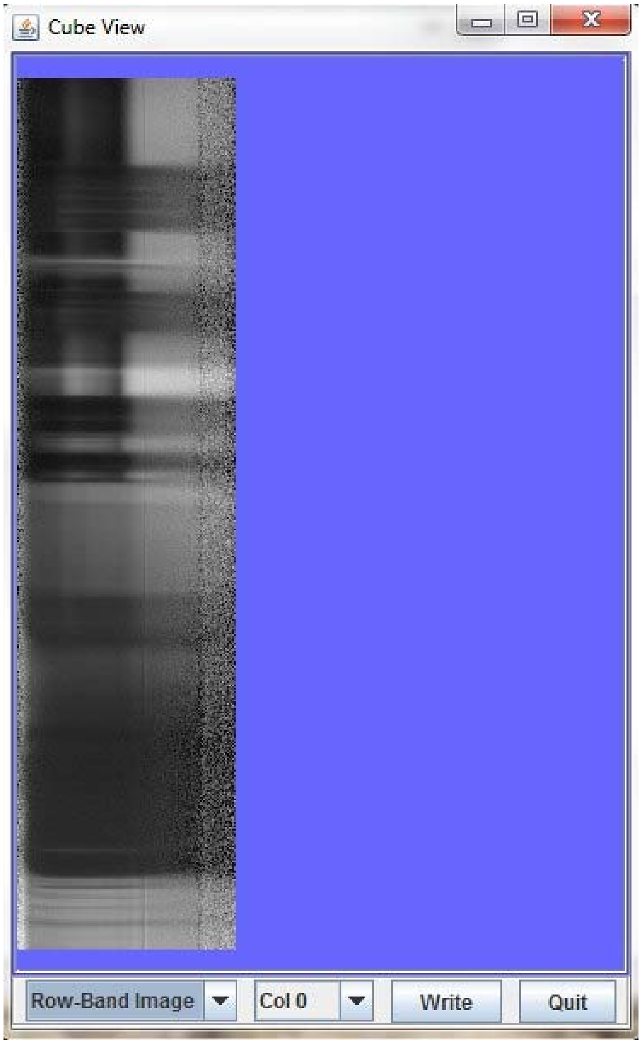

Figure 13: CubeView: Row-Band Image.

5.0 SPECTRAL PROCESSING: THE *FILTER CONTROLS* BOX

The various buttons and combo and text boxes in the *Filter Controls Box*, shown in Figure 14, on the bottom right side of the *Image Tab* provide functions for spectral filtering, spatial filtering, filter selection and display. Spectral filters can be read in from stored text files or can be specified directly from the image using the *Select Region* tool in the software, which is described below.

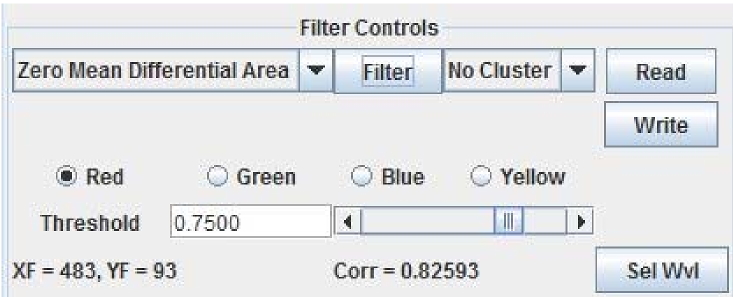

Figure 14: *Filter Controls* Box.

5.1 Defining filters from the Image: the *Select Region* Tool

Checking the *Select Region* check box allows the user to select a spectral filter from the image display panel. The user left-clicks the mouse button on the desired pixel to select that spectrum as the filter kernel. Holding down the mouse button while dragging the mouse across the image selects a region of pixels that are averaged to define the filter.

Figure 15 shows the filter box defined in the *Image Display Panel* and the spectral filter associated with it plotted in the *Spectral Display Panel* in red along with the current pixel's spectrum.

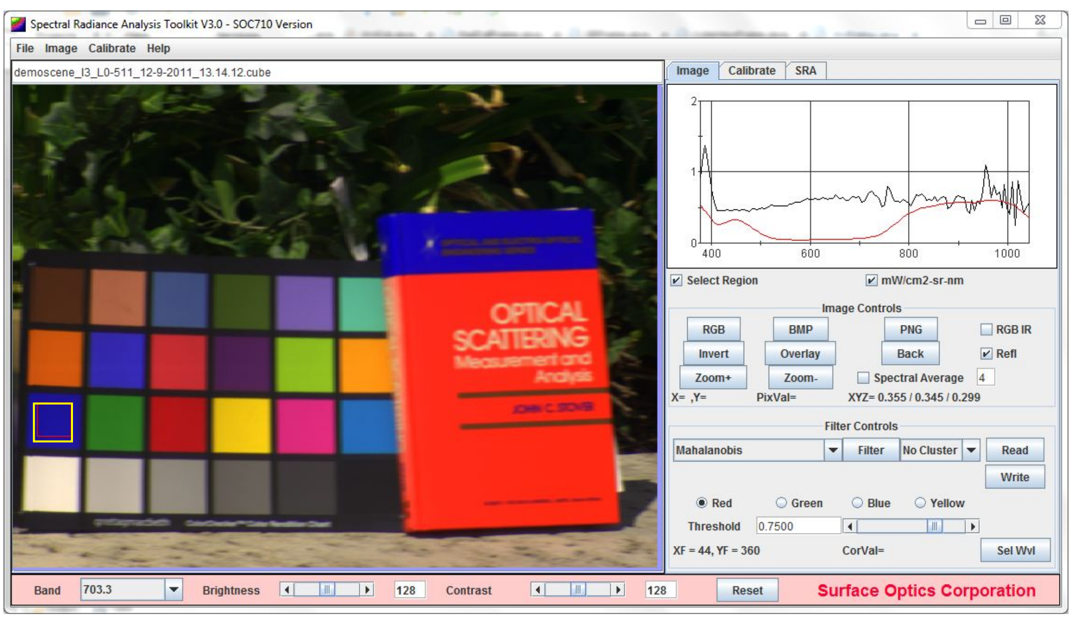

Figure 15: Spectral Filter Selection from Pixels in the Image Display.

The user can also select a region as a polygon by using a series of left-clicks around the desired region of interest. The region is closed by a right click. An example of a region defined using the polygon method is shown in Figure 16, where a leaf has been outlined in the upper left corner of the image.

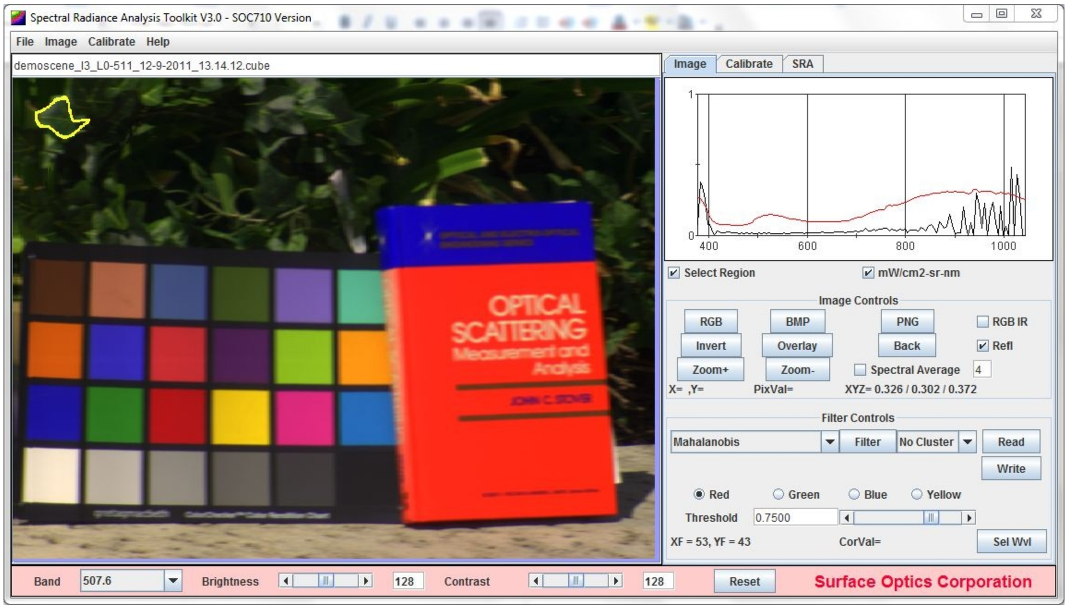

Figure 16: Polygon Region Selection of Leaf in Upper Left Corner of Image.

5.2 Loading and Saving Filters

The *Read* button opens a dialog box for selecting a filter spectrum from a file. The file format is shown in Figure 17. It is simply a header line, followed by a row and column number in the image to reference the filter. This is followed by a sequential, space separated (wavelength, radiance) list of values. The units are defined by the currently selected spectral display option (i.e., counts, radiance or reflectance) and care should be taken to make sure the units of the spectral filter being read in match those of the image to be processed. The row/column value reference is used to correct for the non-linear spectral dispersion (smile) of the instrument. The (row, column) centroid of the selected filter is also displayed in the (XF, YF) label in the filter controls box. The correction formula is stored in the image cube header, and is described in the Data Calibration section.

```
# C:\CD-Data\Software\HSAnalDoc\Data\Parking_Lot140.cube
60 385
397.06 204.41
399.72 173.39
402.38 178.61
        .
        .
        .
```

Figure 17: Spectral Filter Text File Format.

To Save a filter defined using the *Select Region* tool, use the *Write* button in the *Filter Controls* Box.

Typically these filters are defined by selecting a pixel or region of pixels from an image, as described above, and then saved to a file using the *Write* button for subsequent processing in other images. Spectral filters can be specified from other imagers or sources (e.g., data saved from other image cubes) and read in with the *Read* button. The spectral bands do not need to be the same, the code will interpolate to the spectral bands of the current cube. Filters can also be specified from a file of laboratory reflectance measurements, in the format shown above. However, the image cube data will have to be reflectance normalized first.

5.3 Selecting Wavelengths for Processing: *Sel Wvl* Button

Often the user will want to reduce the number of wavelengths used to emphasize some specific phenomenology using only a few bands. The *Spectral Average* function averages bands together to reduce the number of bands. The *SelWvl* button allows the user to select specific wavelengths for processing. Note: a spectral filter must be defined before a set of wavelengths can be selected. The code then proceeds with the spectral processing using only the wavelengths selected. Figure 18 shows the *Select Filter Wavelengths* Dialog Box. Here the user can select to use individual wavelengths, *Save* the selection as a text file, *Read* a previously defined selection, or *Reset* to the use all the wavelengths.

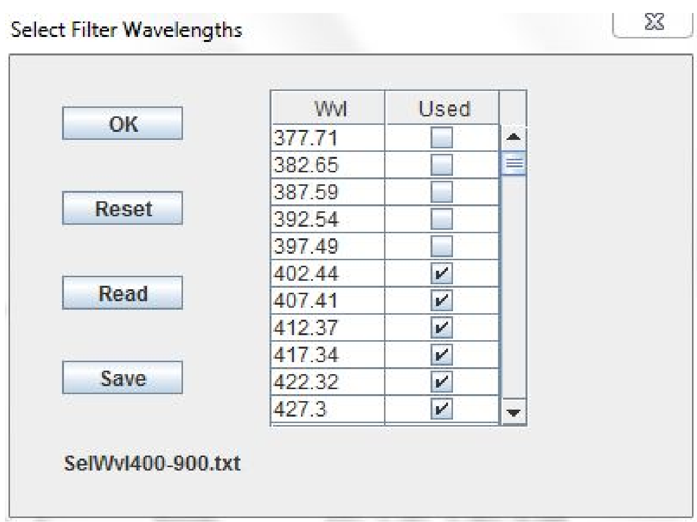

Figure 18: Select Filter Wavelengths dialog box.

5.4 Spectral Algorithm Selection

Given the specification of a spectral filter, an algorithm for pixel-by-pixel spectral detection must be defined. There are many possible algorithms that can be considered (and more are being developed all the time). SRAnal provides two basic types of algorithms that can be used: *statistical*, represented by the *Mahalanobis Distance*, and *vector* represented by *Spectral Angle*

Mapper (SAM) and its variants. The algorithm is selected using the Combo Box shown in Figure 19.

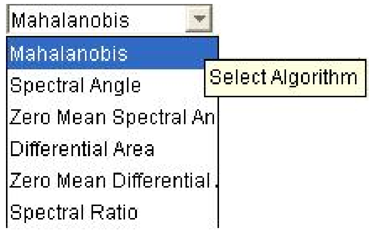

Figure 19: Spectral Algorithm Selection Combo Box Options.

The *Mahalanobis Distance* is a statistical measure of the spectral distance between a pixel and the mean of the spectral distribution defined from the spatial selection of the spectral filter (i.e., training set). The training set is used to compute the statistical spectral covariance matrix. The *Mahalanobis Distance* (squared) is defined to be the inverse of the covariance matrix, pre- and post- multiplied by the unknown pixel spectrum minus the mean spectrum of the training set,

$$D^2 = (\boldsymbol{x} - \boldsymbol{\mu})' \; S^{-1}(\boldsymbol{x} - \boldsymbol{\mu}),$$

where S is the covariance matrix of the training set, and D is the *Mahalanobis Distance* of the point $\boldsymbol{x}$ to the mean $\boldsymbol{\mu}$ of the training set distribution. Note, because calculating the *Mahalanobis Distance* requires a matrix inversion, the training region selected must have at least the same number of points as spectral bands, otherwise an error message will be generated in the *Filter Controls* text label.

The *Spectral Angle Mapper*, or dot product, algorithm is a very simple filtering algorithm that treats each spectral radiance as an N-dimensional vector and simply computes the angle between the two vectors by dividing the dot product of the two vectors by each vector's magnitude. Formally, this algorithm is given by

$$C_{DOT} = \frac{\sum L(\lambda_n) \bullet F(\lambda_n)}{\sqrt{\sum L(\lambda_n)^2 \bullet \sum F(\lambda_n)^2}}$$

where $L(\lambda_n)$ is the measured spectral radiance at the nth wavelength, and $F(\lambda_n)$ is the filter spectral radiance at the nth wavelength. Subtracting the mean value from both the filter and spectral radiance at each pixel provides the *Zero Mean (ZM) Spectral Angle* algorithms.

Another completely different type of vector matching algorithm can be formed by normalizing both the measured and filter radiance such that each encloses unity area, and subtracting the area "trapped" between the two curves from 1.0. For two identical spectral radiance, zero area will be "trapped", and the correlation value will be 1. As more and more area lies between the two curves, the correlation value will become smaller and smaller. This is the *Differential Area* algorithm. By subtracting the mean from each spectral radiance value and using the resultant radiance values in the above algorithm yields the *Zero-Mean (ZM) Differential Area* algorithm.

The *Spectral Ratio* algorithm computes the correlation as one minus the sum of the difference between the ratio of the radiance to the filter from the mean ratio.

5.5 *Filter* Button and Color options Check Box

The *Filter* button tells the software to perform the spectral correlation based on the selected algorithm and spectral filter. The result is a correlation map image, for the current threshold setting, and is displayed in the image window. The spectral correlation threshold setting is specified using the Text Box and Slide Bar shown in Figure 20.

Figure 20: Spectral Correlation Threshold Setting.

An example of a spectral correlation processing result using the *Zero Mean Differential Area* algorithm on a filter spectrum selected from natural vegetation (leaf) is shown in Figures 21 and 22, below.

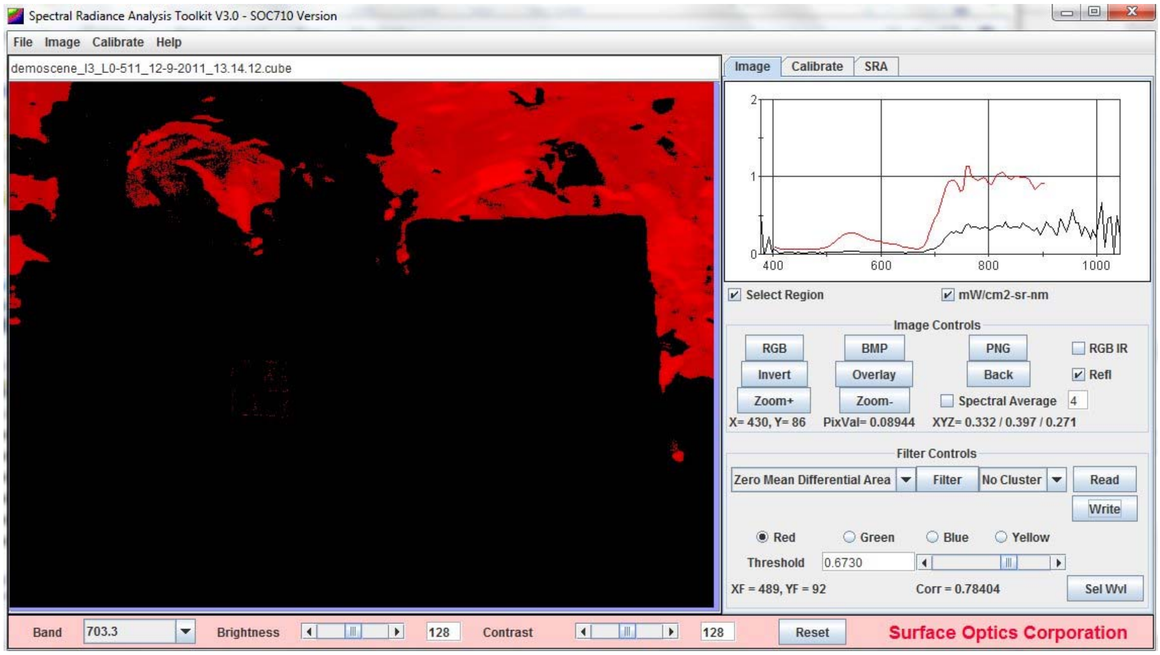

Figure 21: Spectral Correlation Results Image Display.

The image window in Figure 21 shows highlighted pixels, which are defined as a result of the spectral correlation processing, and the threshold level specified. In this case, the real plants are highlighted based on the spectral filter selection shown. The Spectral Plot display now shows the spectral radiance of the pixel pointed to in the image as well as the spectral filter function in red.

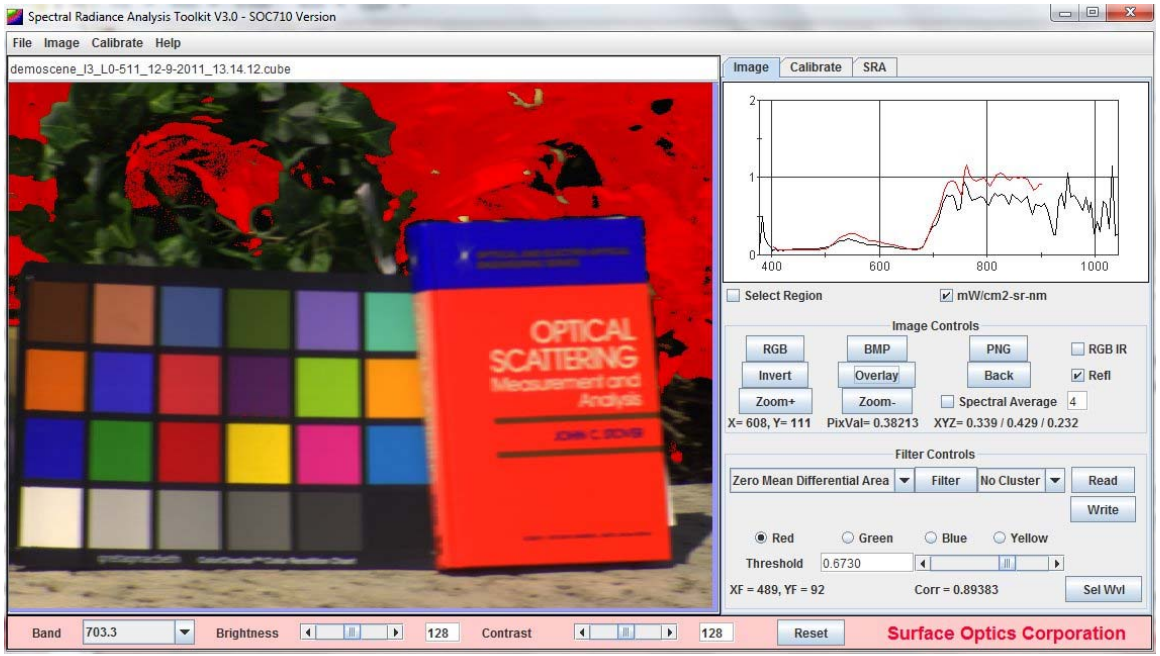

Figure 22: Spectral Correlation Map Overlaid on RGB Display.

The image window in Figure 22 shows the highlighted pixel clusters which have been *overlaid* on the RGB image. The highlighted pixels are defined as a result of the spectral correlation using the Zero Mean Differential Area Algorithm. In this case only wavelengths between 400 and 900 nm were used using the *SelWvl* option to eliminate noisy data.

5.6 Additional Filters: Red, Green, Blue and Yellow

It is possible to perform correlations for up to four filters using the *Red*, *Green*, *Blue* and *Yellow* radio buttons. A separate spectral filter can be assigned to each button along with a separate threshold by selecting a color and performing the steps as outlined above for processing the data.

The following is an example of using the *Blue* filter along with the *Red* filter from the example above to show multiple correlation filters. The user first selects another region of interest, in this case the artificial plants, and down selects the bands to be between 400 and 900 nm to eliminate noisy data. After selecting the color blue and applying the filter the result is shown in Figure 23.

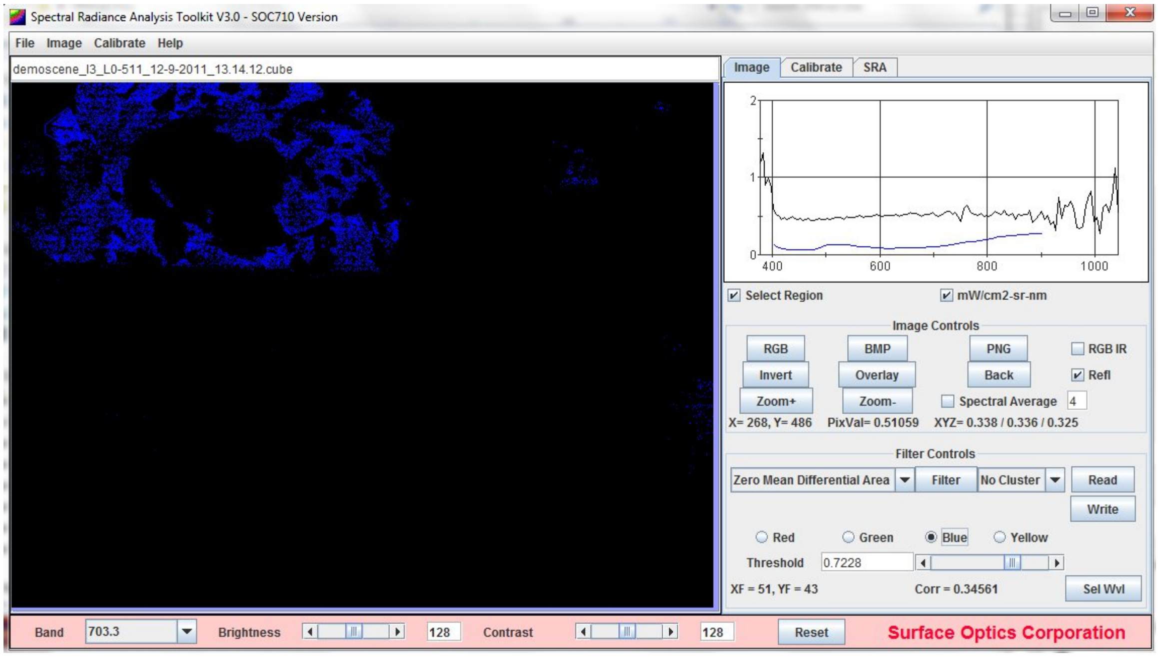

Figure 23: The Results of Mahalanobis Processing on a Spectral Filter from the Fake Leaves.

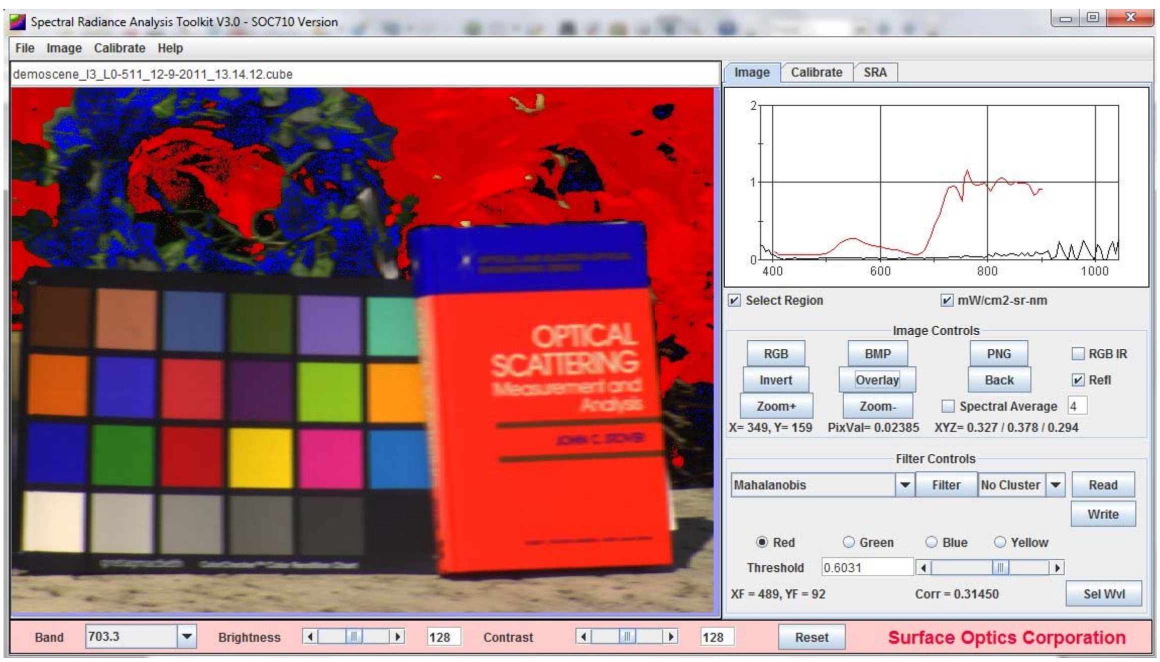

Figure 24: Overlay Results for the Red and Blue Filters.

5.7 *Cluster* Function

The *Cluster* function performs a first order spatial clustering of the image which can be used to refine a classification. Typically, any spectral classification will result in pixels which are considered *True* and *False*. *True* matches are those matches which are on the object which you are looking for in the image. *False* matches are those that are not. Fortunately, in many cases, False matches are interspersed across an image and are not concentrated spatially in any one area, while *True* matches generally are. The cluster function returns the largest spatial clustering of matches above the spectral threshold, thereby rejecting many of the *False* matches contained in a processed image. The following images show examples of the spatial clustering algorithm in use.

In the example below, a spectral filter was defined from the blue band across the top of the book. Using the Zero Mean Differential Area algorithm, Figure 25 shows the overlay of the correlation results. There are *False* matches on the light blue patch on the color panel, which is referred to as spectral clutter. The target object, the blue top on the book, shows a much higher degree of correlation, as you would expect. The Cluster function can be used to eliminate the *False*, clutter region.

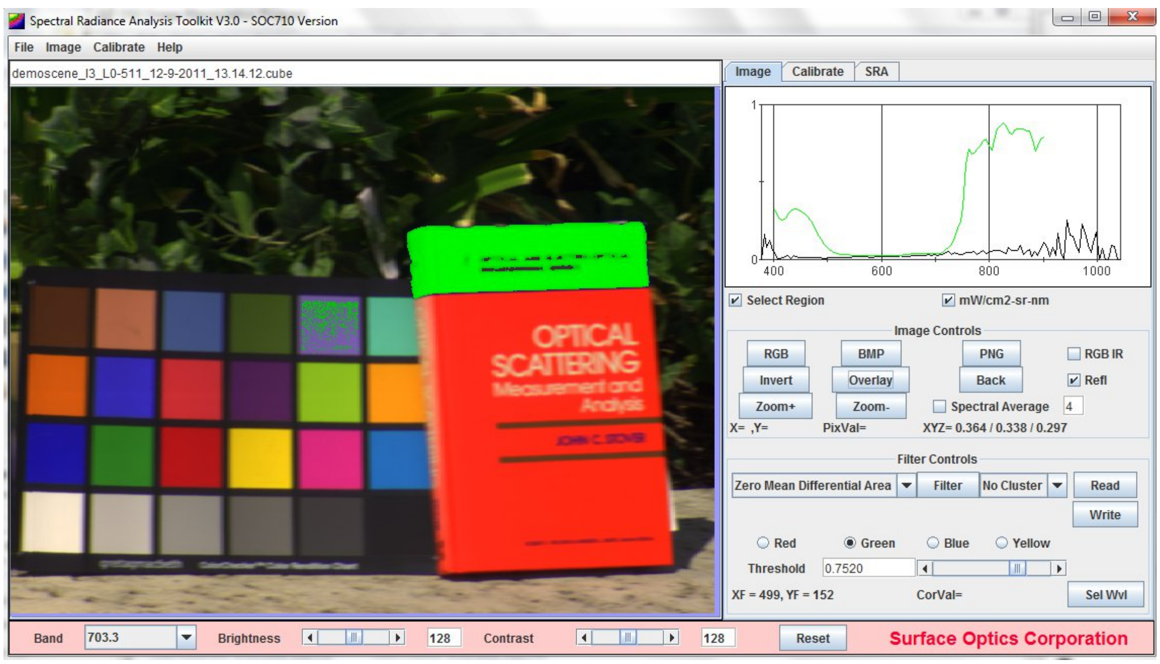

Figure 25: Result of a Spectral Correlation Showing Spectral Clutter on the Light Blue Color Patch.

By selecting the *Cluster* option in the Combo Box and clicking the filter button, the software searches for the largest spatial cluster of spectral matches which in this case is the blue band on the book. In Figure 26, the results of the spatial clustering refinement are shown, eliminating the clutter on the light blue patch.

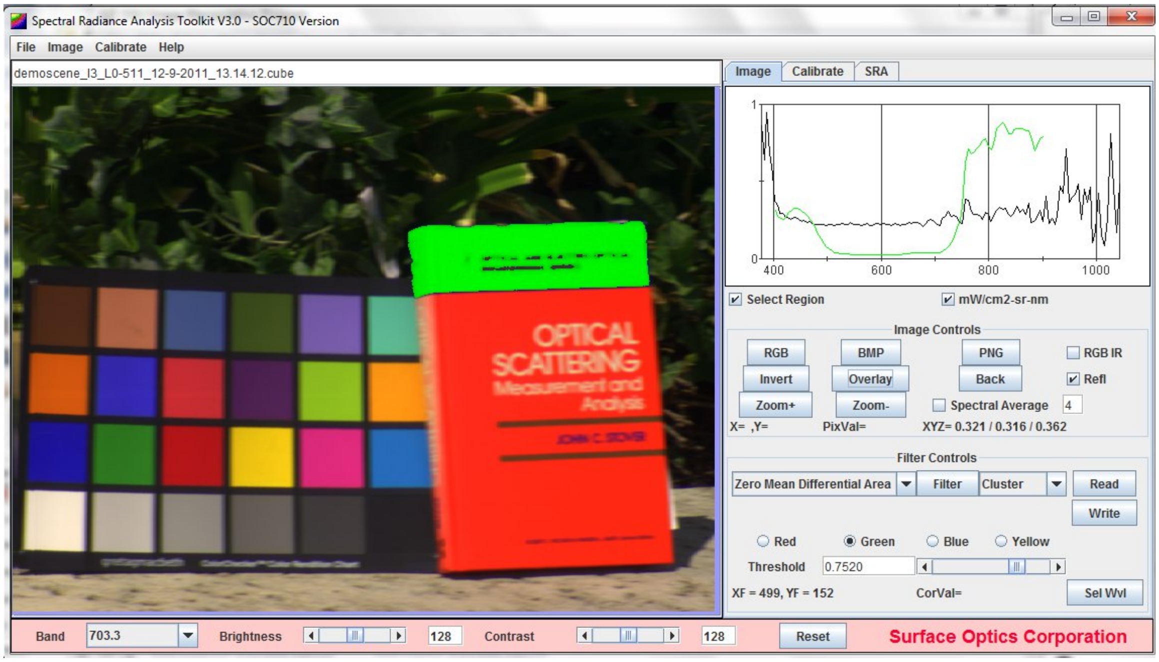

Figure 26: After Spatial Clustering.

6.0 CALIBRATING IMAGES: *CALIBRATE* MENU/TAB

The SOC-710 system is fully calibrated at the factory and calibration files are provided with the system installation. Hyperspectral image cubes saved from the SOC 710 imager are calibrated in a three step process. The calibration steps include spectral calibration, dark level offset correction and spectral and spatial radiometric calibration. These functions are accessible through the *Calibrate* panel tab on the SRAnalysis Toolkit software, shown in Figure 27. These functions are also available on the pull down *Calibrate* menu item.

Additionally, if a material of known reflectance is in the image, such as the color panel shown in the figure, this can be used to perform a reflectance normalization correction. These steps will be described in detail, below.

The fundamental philosophy of our calibration process is to maintain the integrity of the raw data. All of the specific data introduced during calibration is stored in the image cube file header or footer. All of the calibration steps can be reversed if a wrong file is introduced, or the instrument is out of calibration, so that no raw data is lost and the image can be recalibrated using the correct files. However, a fully calibrated image cube, which cannot be un-calibrated, can be saved as four byte floats, using the *Save Float* button, for processing in other applications.

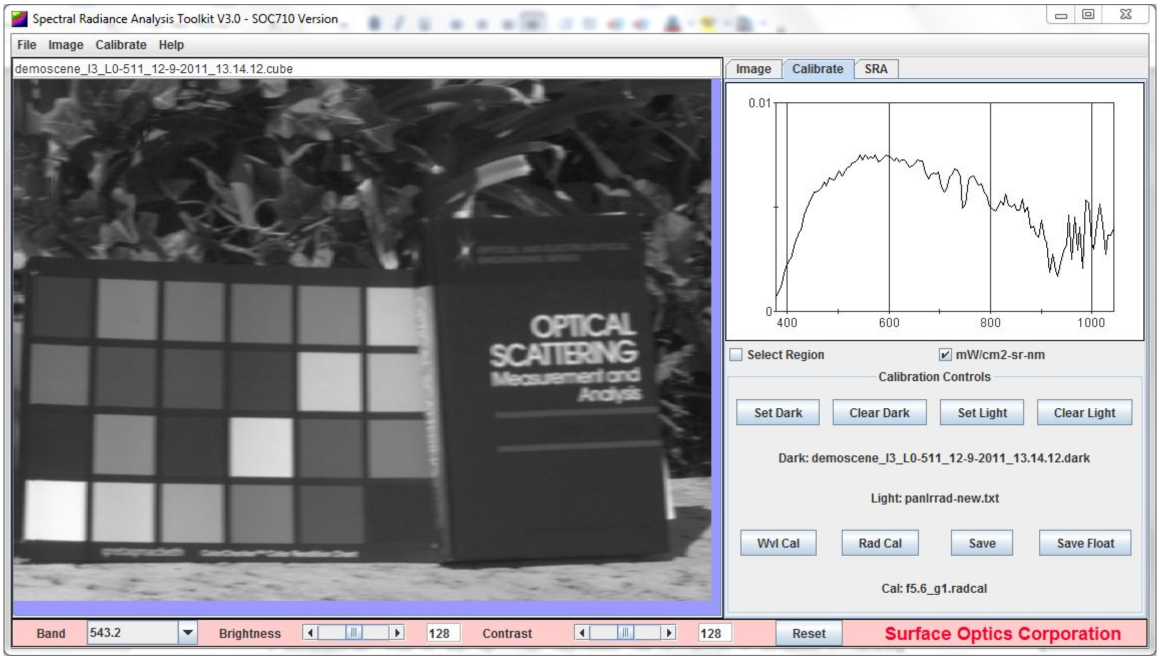

Figure 27: SRAnalysis Calibration Tab.

6.1 Spectral Calibration

Wavelength calibration of the SOC-710 system is performed at the factory using monochromatic light sources and the results are included in the file: DefCalLite.txt. Normally, this file is stored in the working directory for the SOC-710 system software and is automatically read on start-up. This calibration can be viewed or modified by clicking on the *WvlCal* button in the *Calibration Control Box*. Figure 28 shows the Wavelength Calibration dialog box.

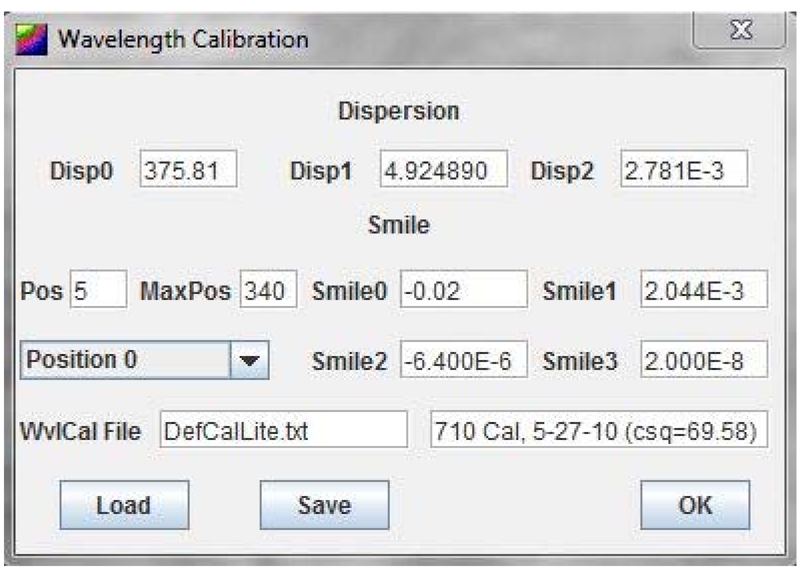

Figure 28: Wavelength Calibration Dialog Box.

The parameters, *Disp0*, *Disp1* and *Disp2* are used to calibrate the spectral dispersion of the spectrometer. *Disp0* is the first wavelength in nanometers of the data set, *Disp1* is the linear dispersion, in nanometers, per band and *Disp2* is a second order correction term.

The parameters: *Pos*, *MaxPos*, *Smile0*, *Smile1*, *Smile2* and *Smile3* are used to correct for non-linear optical distortions that affect the actual wavelength measured at a particular position on the FPA. In the spectrometer, the light from the foreoptic passes through a slit, on to the grating, which disperses the light on the FPA. Ideally, the slit images as a straight line on the FPA; in practice, optical distortions in the system bend the image of the slit into a curve. This effect is referred to as "smile."

The smile is corrected in the data using a third-order equation based on the position in the FPA. The smile parameters are fit at three positions (rows) in the array, and the values are interpolated for other positions. The smile parameters for each position can be viewed/modified using the *Position* Combo Box. The points where the smile curves are fit are given by the *Pos* parameter. The maximum row where a particular wavelength is detected is the *MaxPos* parameter. The *Smile0*, *Smile1*, *Smile2* and *Smile3* parameters are a third order equation that calculates the fractions of a pixel (row) shift (using the dispersion equation) based on the difference between the column and *MaxPos*.

The text boxes in this Wavelength Calibration window can be directly modified by the user, and the *Load* and *Save* buttons allow for updating and recalling this data. Figure 29 shows an example of the format of this file.

```
#Default Calibration file (WvlCal.txt csq=5.02)
397.06 2.656062 0.001293
 15 491 -0.01  0.00099822 -3.00E-8  1.0E-9
 55 509 -0.04  0.00111717  2.53E-6  0.0
 88 609  0.04 -0.00139172  1.00E-5 -1.0E-9
```

Figure 29: Example DefCalLite.txt.

6.2 Dark Level Offset Correction

The FPA and associated electronics of the imaging system produce a level of electronic noise in the image which needs to be removed. The electronic noise will be dependent on operating conditions (e.g., ambient temperature), how long the instrument has been operating and, most importantly, the integration time used in capturing the image. This dark noise data should be routinely recorded and saved at, or near, the same time as the image data collection.

The dark file is collected by physically blocking the light path to the FPA and taking and saving a small image cube (~25 lines). This file is generally stored with the same image file name with a *.drk* extension. The data is applied as an offset correction by simply clicking the *Set Dark* button and navigating to the file. The dark data can be easily removed using the *Clear Dark* button.

6.3 Spatial and Spectral Radiometric Calibration

The optical throughput of the system varies as a function of spatial and spectral position on the FPA. Optical effects such as vignetting (a drop in intensity along the borders of the array), the spectral response of the optics, grating dispersion element and the spectral response of the FPA itself all combine to modify the measured spectral and spatial radiances of the scene. For the SOC-710 system, the FPA is translated across the image of the spectrometer slit so that the calibration must be performed for each row and column of the system.

The gain calibration array is determined by capturing a uniform image from a known, calibrated illumination source. This is performed in the factory by capturing an image of the exit aperture of the LabSphere Uniform Source calibration sphere.

Uniformity (gain) calibration files are prepared at the factory and are provided with the system. The gain calibration is applied using the *Rad Cal* button in the Calibration box. This button opens the *Rad Cal Display* window, shown in Figure 30. The Rad Cal window has two functions, one performs "cal-ing" and "uncal-ing" (if necessary) an image during a processing session. The other allows the user to prepare their own calibration files given suitable image cubes captured from a calibrated integrating sphere, and is described elsewhere.

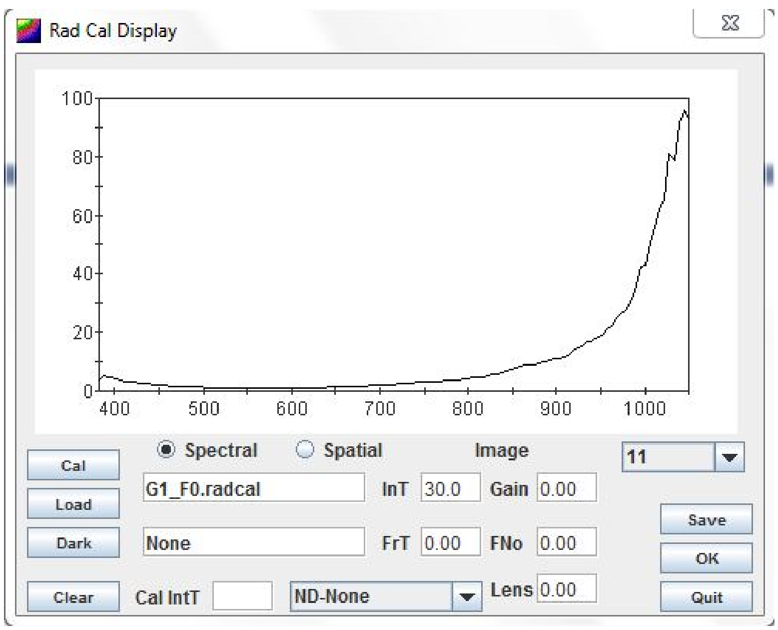

Figure 30: Spectral - Spatial Gain Calibration Window.

Gain calibration files have been measured and prepared at the factory and are stored as ".cal" files in the SOC-710 system folder. These calibration files are large (180 Mbytes) to accommodate the gain correction for each pixel row and column in the image. A copy of the appropriate gain calibration file must be stored in the same folder as the data cubes. When saving a calibrated image cube, the file name is stored in the header. Subsequent processing on the cube will read in the gain file stored with the cube data.

Figure 31 shows the Rad Cal Display window with the important buttons/information required for calibration highlighted. The simple procedure to apply this calibration correction to the image is to enter the image integration time and then press the *Cal* button in the *Rad Cal Display* window to open a dialog box for reading this data, then press the *OK* button to apply the calibration and return to the main application.

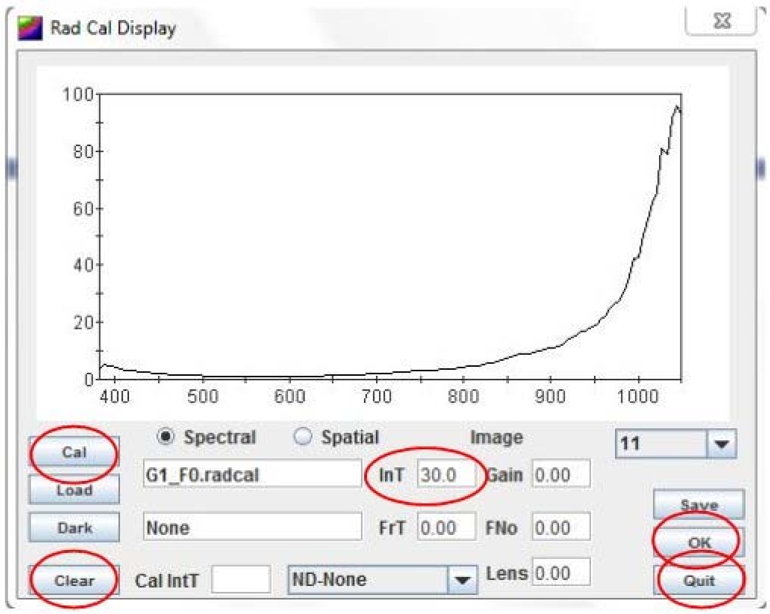

Figure 31: *Rad Cal Display* Window with the Key Buttons Highlighted.

The text boxes under the spectral display in this window record a number of parameters relevant to the imaging sensor: Integration Time (*InT*) in milliseconds is the time to capture each line in the image, Frame Time (*FrT*) in milliseconds is the time to capture a complete image frame (some number of lines), *Gain* is the gain setting on the electronics, *F/No* is the f-number of the optical system, and *Lens* is the focal length of the foreoptic. Except for the integration time (*InT*), these values are stored in the file header for information only and do not affect the gain correction. The preprocessed calibration data has been normalized by the integration time of the raw calibration image (*Cal InT*) so that reading a .cal file only requires input for the integration time of the image that is being calibrated *(IntT*). Note: The *InT* value must be specified before a .cal file can be read.

The graphic display in Figures 30 and 31 show the gain factor for each spectral point in the image. The Combo Box on the right allows the user to select the spatial column to view the gain calibration. The shape shows the spectral drop off in efficiency of the spectrometer at the long and short wavelengths, which is corrected using this gain factor.

The *Spectral* and *Spatial* radio buttons below the graph allow the user to view the gain calibration in either the spectral or spatial dimension. Figure 32 shows the graph of the gain correction plotted versus column. The Combo Box now selects the wavelength to view gain function. The slight bend in this curve is the correction of optical vignetting in the system.

The *OK* button saves the gain calibration information in the image cube header and returns to the main application. The *Clear* button resets the gain array to unity, thus "un-cal-ing" the image. The *Quit* button returns to the main application, without modifying the gain correction.

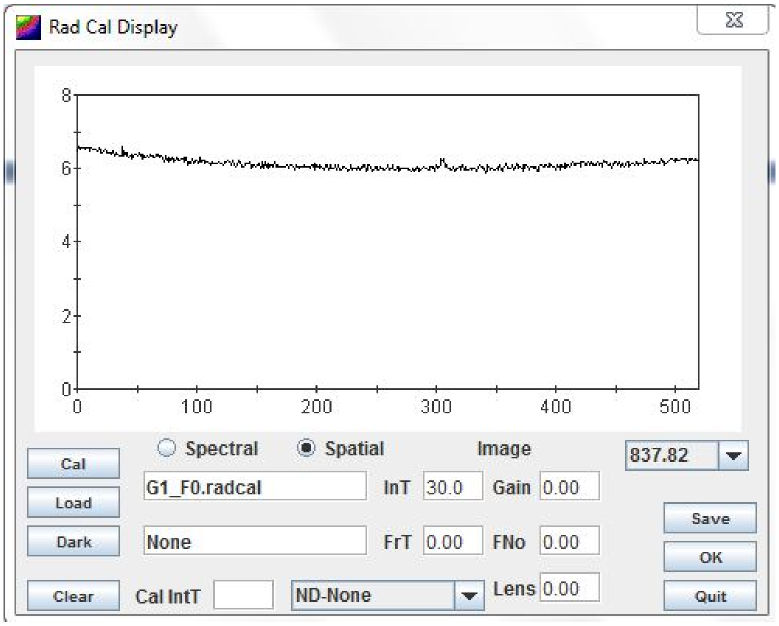

Figure 32: Spatial gain calibration display.

6.4 Reflectance Calibration (Normalization)

Many applications require an additional calibration step to obtain estimates of material reflectances in the image. This is an extremely complicated task to do exactly, but a simple reflectance calibration can be performed from the image data itself if a suitable material is identified in the image with known reflectance.

Starting from the simplified radiance equation for a pixel,

$$L_\lambda = R_\lambda * S_\lambda * A_\lambda * O_\lambda$$

where,

R – is the material reflectance

S – is the spectral solar irradiance

A – spectral atmospheric transmission, radiance

O – is the spectral optics transmission

and, using the measurement of the pixel radiance of the standard material, also in the image,

$$N_\lambda = R^n{}_\lambda * S_\lambda * A_\lambda * O_\lambda \quad ,$$

then, given the lab measured reflectance, $R^n{}_\lambda$, of the standard, the unknown reflectance is obtained from the ratio

$$R_\lambda = L_\lambda * R^n{}_\lambda / N_\lambda \quad .$$

Once an image has been reflectance calibrated, secondary standards can be defined in the image for subsequent image analysis without the lab standard in place.

Reading in the reflectance of the reference material used for reflectance normalization is accessible through the *Norm Reflectance* pull down menu option from the Calibrate menu. The code assumes a default 0.98 reflectance (which is essentially the lowest white square in the reference card shown in Figure 33. But any laboratory measurement can be input in the format shown in Figure 34. This is simply a header line, a line of two integers (not used) and then a space separated table of wavelength (in nanometers) and reflectance (0 to 1). The wavelengths do not have to match those of the imager since the code interpolates onto the spectral bands of the imager. The reflectance data must be read in for each cube processed because the code reverts to the default value when opening a new image cube.

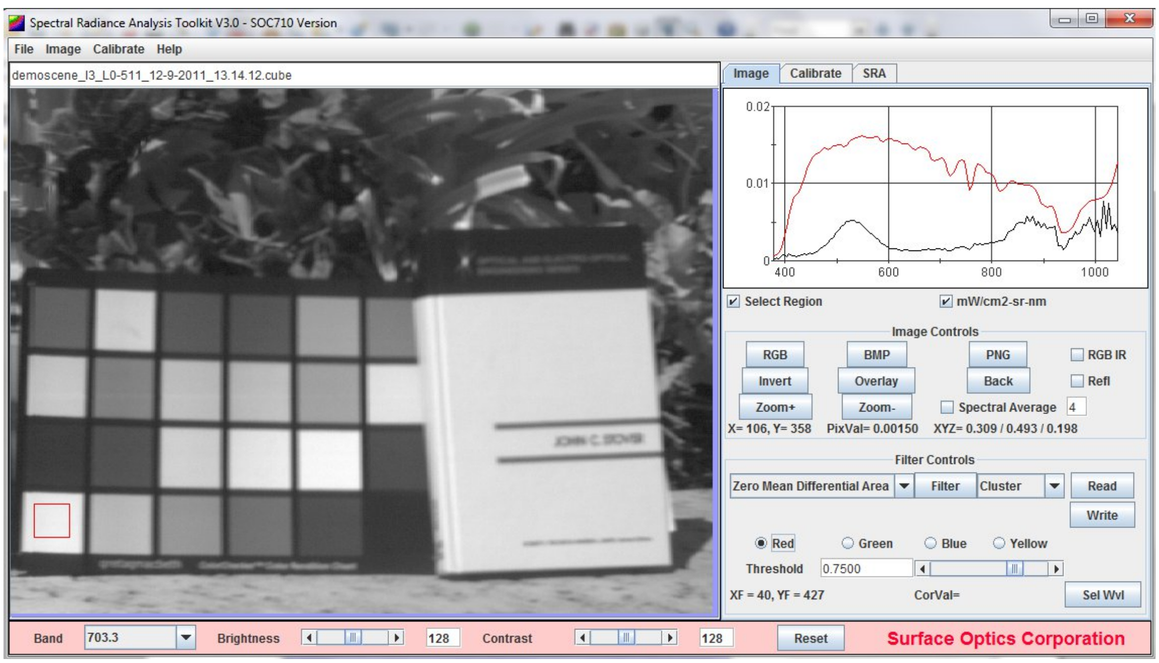

Figure 33: Calibration using Normalization Function.

Given the reflectance of the reference material has been identified, an averaged calibrated radiance spectrum of this material must be recorded and saved. This is done using the filter controls on the *Image* tab. First the *Select Region* check box must be checked. Then dragging the mouse over the reference material will average the radiance in the box and provide an estimate of N_λ, as shown in Figure 33. Save this as a text file using the *Write* button in the Filter controls. Finally, read this file in using the *Get Light* button on the calibrate tab or through the pull down menu controls. Now the *Refl* check box on the *Image* controls tab allows the user to toggle between reflectance and radiance display mode. Figure 35 shows the RGB image of the scene in reflectance mode. This procedure can be reversed using the *Clear Light* button.

Figure 34: Example of Format of Norm Reflectance Data used in Reflectance Calibration.

```
# white Reference Material reflectance
 0  0
403.55   0.977874
408.57   0.987298
413.58   0.984065
418.60   0.983595
423.63   0.982206
428.66   0.986709
433.70   0.983718
438.74   0.985206
443.78   0.984265
448.83   0.984847
453.89   0.984596
458.95   0.985571
464.01   0.984767
469.08   0.983647
474.15   0.983972
479.23   0.984761
484.32   0.983890
489.40   0.984848
494.50   0.982815
499.60   0.983556
504.70   0.983542
509.81   0.984575
514.92   0.984468
520.04   0.984243
525.16   0.983483
530.29   0.981219
535.42   0.982662
540.55   0.985224
545.69   0.984219
550.84   0.984090
555.99   0.982929
561.15   0.982889
```

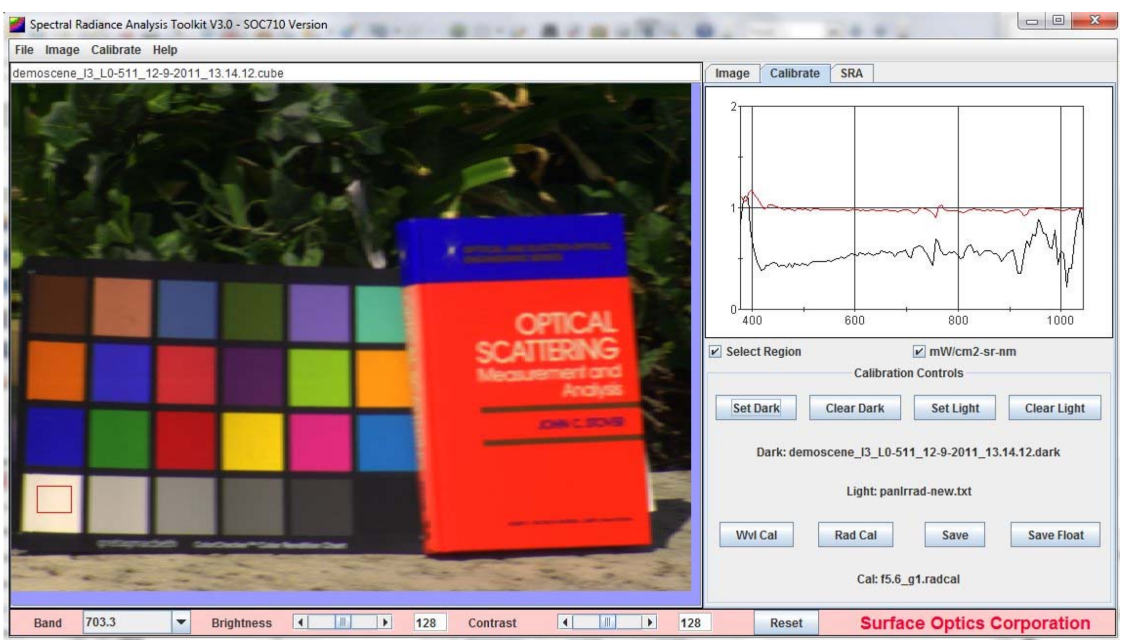

Figure 35: Reflectance Calibrated Image.

6.5 Calibration Procedures: Producing the Cal Files

The SOC-710 is fully calibrated before delivery, and can be returned to SOC for recalibration. Some users with the proper calibration sources and standards might prefer to perform this procedure themselves. The SRAnal software has the capability to process the calibration data to produce the spectral and radiometric calibration files.

6.6 Wavelength Calibration Procedure

The procedure for calculating the spectral dispersion of the SOC-710 starts with taking a sequence of spectral images from a nearly monochromatic light source. At the factory, this is performed using an ISA monochrometer, which has been separately calibrated using Oriel calibrated arc lamp sources. Figure 36 shows a calibration image recorded when the monochrometer was set to pass 550 nm light.

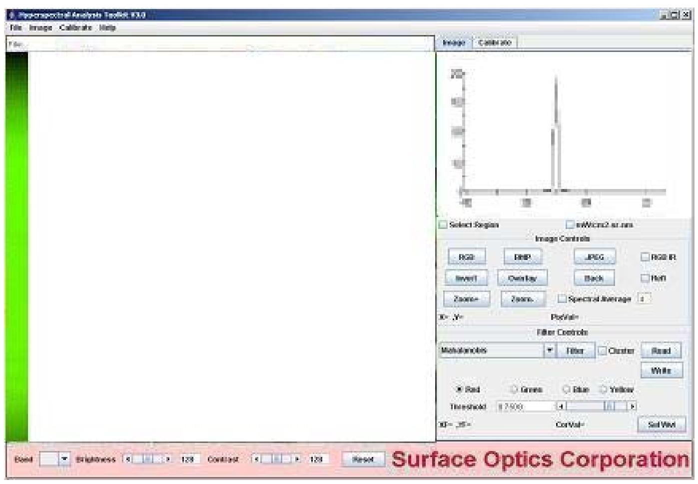

Figure 36: A Wavelength Calibration Data Set Example.

The *Avg Image* menu item in the *Calibration Menu* was used to average multiple columns of this uniform image to increase the signal to noise. Using the right mouse button to click on a pixel in the image brings up the *Spectrum Display/Fit* window, shown in Figure 37, which has a set of tools for performing the wavelength calibration.

<u>Note: the *Select Region* check box must be unchecked to bring up the *Spectrum Display/Fit* window.</u>

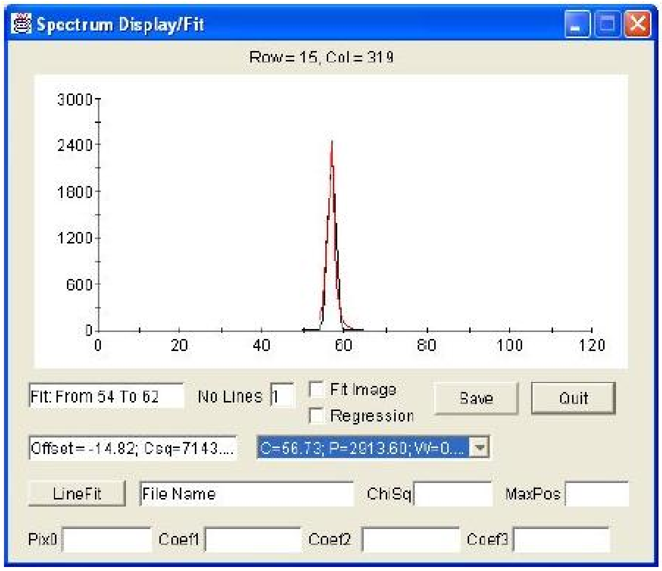

Figure 37: Spectrum Display/Fit Tools.

The plot in the *Spectrum Display/Fit* window is the raw data for the image row and column displayed at the top of the window. Dragging the mouse (holding down the left mouse button) across the plot display selects a number of spectral points that are used to fit single (or multiple) Lorentzian lines to the data. The number of lines fit is defined in the *No Lines* text box. The text box to the left of the *No Lines* display indicates the fit range. The fit results are indicated in the text and combo boxes immediately below the *No Lines* display.

The algorithm goes through the fit range and selects the *No Lines* largest peaks as starting points and uses a Levenberg-Marquardt non-linear technique to obtain a best fit to the data. The purpose is to estimate the position of the peak center, which generally doesn't fall on a particular pixel. The combo box lists the peak center (*C*), peak strength (*P*) and width (*W*) parameters for each line fit. The red curve shows the fit results for the selected range plotted and compared to the data.

This data is manually recorded as a series of wavelengths and peak center positions and saved in a separate file. An example of this data is shown in Figure 38.

410	4.5
420	8.5
430	12.5
440	16.4
450	19.7
500	38.4
550	56.7
600	73.5
650	91.4
700	108.4

Figure 38: Example Wavelength Calibration Data.

The *LineFit* button opens a File Dialog Box for reading this data. The code then performs a linear least squares fit to a second order equation to define the dispersion parameters for the system. The results are displayed in the Text boxes labeled: *Pix0*, *Coef1* and *Coef2*, shown in Figure 39, which are in fact the *Disp0*, *Disp1* and *Disp2* dispersion parameters. The wavelength at each pixel position, *P*, is then given by

$$\lambda = Disp0 + Disp1 * P + Disp2 * P^2$$

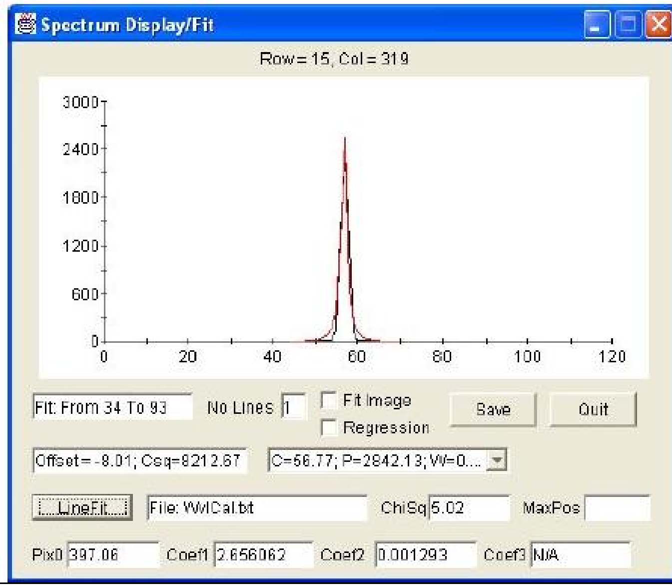

Figure 39: Dispersion Fit Results.

6.7 Smile Calibration Procedure

Because of the non-linear optical effects in the system, known as “smile,” the dispersion equation defined above is not correct for all spatial positions (columns) in the image. Ideally, a dispersion equation would be defined for each of the 524 columns in the image. This is not practical, however, and the approach is to fit a third order equation to the measured “smile” displacement and correct the measured wavelengths on the fly. The equation used to fit the smile calculates the shifted pixel position, *Ps*, used in the dispersion equation as a function of column position, *C*, in the array.

$$P_S = P + Smile0 + Smile1 * k + Smile2 * k^2 + Smile3 * k^3$$

where, $k = |\, MaxPos - C \,|$.

Figure 40 shows the Lorentz line fit to the 546 nm line from a calibrated Hg-Ar lamp source imaged from the integrating sphere. An integrating sphere must be used for this calibration step to insure that all pixels are uniformly illuminated.

Checking the *Fit Image* check box in the window performs this fit for each column in the image. The graphic display, shown in Figure 34, changes from a spectral plot to a spatial plot showing the pixel shift as a function of the absolute value of the difference between the maximum peak position and the peak position obtained for each column in the image.

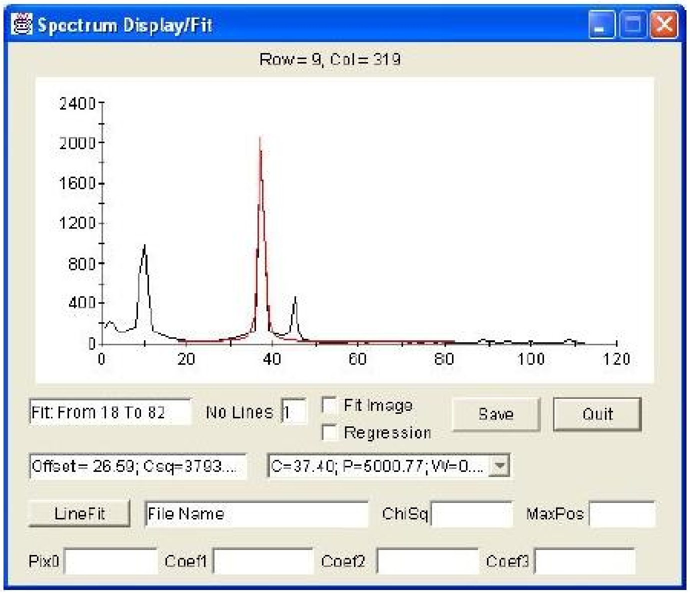

Figure 40: The 546 nm Line from the Hg-Ar Lamp Source used for the Smile Calibration.

The shape of the shift of the peak position as a function of image column shown in Figure 41 is a graphic illustration of the "smile" of the imaging system. Checking the *Regression* check box performs a linear least squares fit of the third order equation to this data.

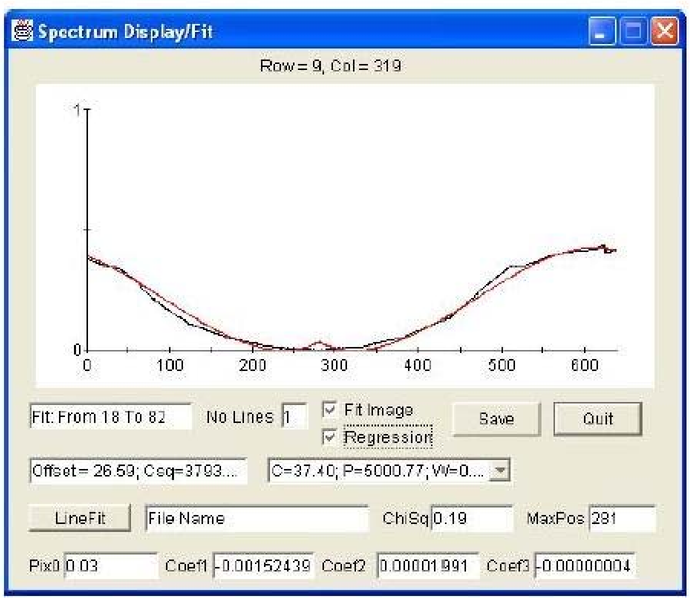

Figure 41: Smile Correction Curve Fit.

The results of the fit are shown as the red curve in the graphic display and the parameters listed in the text boxes along the bottom of the window: *Pix0*, *Coef1*, *Coef2* and *Coef3* are identified as *Smile0*, *Smile1*, *Smile2* and *Smile3*, respectively.
Because the "smile" can change as a function of position on the array, this procedure is repeated for a number of incident wavelengths (i.e., spectral positions) on the array. At present, the "smile" is fit at three positions (rows) in the array, chosen by input wavelength, and the smile parameters are interpolated for the other positions. The smile parameters are chosen based on the quality of the fit and consistency for interpolation (i.e., no wild changes in the parameters from position to position).

6.8 Uniformity (Gain) Calibration File

The optical throughput of the system varies as a function of spatial and spectral position on the FPA. Optical effects such as vignetting (a drop in intensity along the borders of the array), the spectral response of the optics, grating dispersion element and the spectral response of the FPA itself all combine to modify the measured spectral and spatial radiances of the scene. The RGB image of an uncalibrated data cube, shown in Figure 42, has a distinct yellow cast to it due to the non-uniform spectral response of the system.

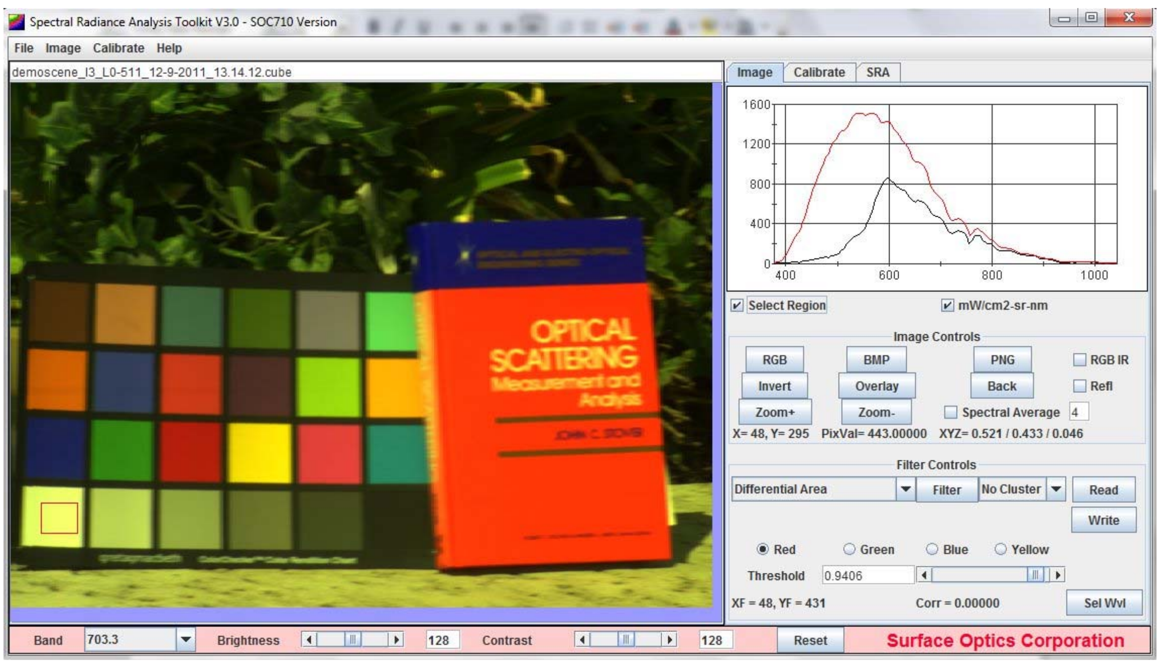

Figure 42: RGB Image Without Uniformity Calibration.

The gain calibration array is determined by capturing a uniform image from a known, calibrated illumination source. This is performed by capturing an image of the exit aperture of the LabSphere uniform source calibration sphere.

The text boxes, in Figure 43, under the spectral display in this window record a number of parameters relevant to the imaging sensor: Integration Time (*InT*) in milliseconds is the time to capture each line in the image, Frame Time (*FrT*) in milliseconds is the time to capture a complete image frame (some number of lines), *Gain* is the gain setting on the electronics, *F/No* is the f-number of the optical system (typically fixed at F/2.8 for the SOC-710 system) and *Lens* is the focal length of the foreoptic (typically fixed at 70 mm for the SOC-710 system). Except for the integration time (*InT*), these values are stored in the file header for information only and do not affect the gain correction.

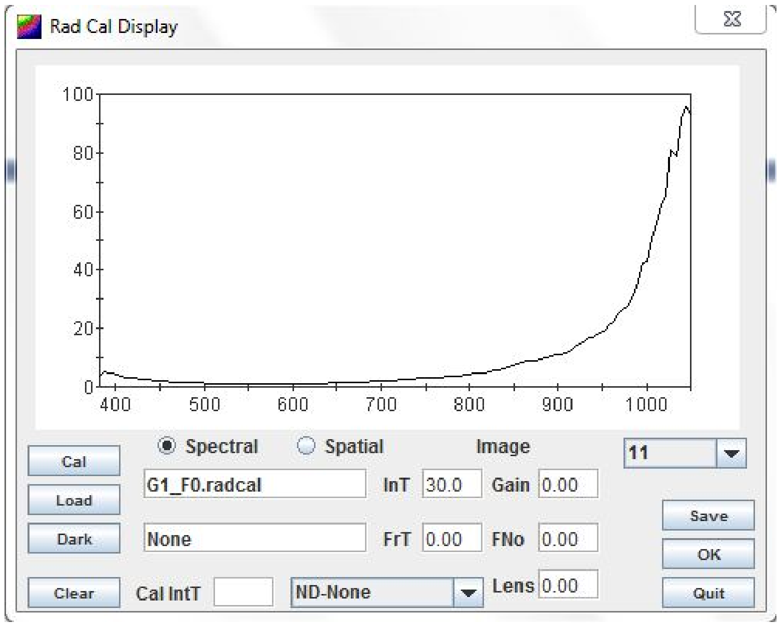

Figure 43: Spectral Gain Calibration Display.

The other significant data item required to perform the calibration is the integration time of the calibration image, *Cal IntT*, in milliseconds. The radiometric calibration is based on the ratio of the integration time for the response to the known spectral source radiance to the integration time used for the unknown radiance of the image cube.

The preprocessed calibration data has been normalized by the integration time of the raw calibration image (*Cal InT*) so that reading a .cal file only requires input for the integration time of the image that is being calibrated *(IntT*). Note: The *InT* value must be specified before a .cal file can be read.

The graphic display in Figure 43 shows the gain factor for each spectral point in the image. The Combo Box on the right allows the user to select the spatial column to view the gain calibration. The shape shows the spectral drop off in efficiency of the spectrometer at the long and short wavelengths, which is corrected using this gain factor.

The *Spectral* and *Spatial* radio buttons below the graph allow the user to view the gain calibration in either the spectral or spatial dimension. Figure 44 shows the graph of the gain correction plotted versus column. The Combo Box now selects the wavelength to view gain function. The slight bend in this curve is the correction of optical vignetting in the system.

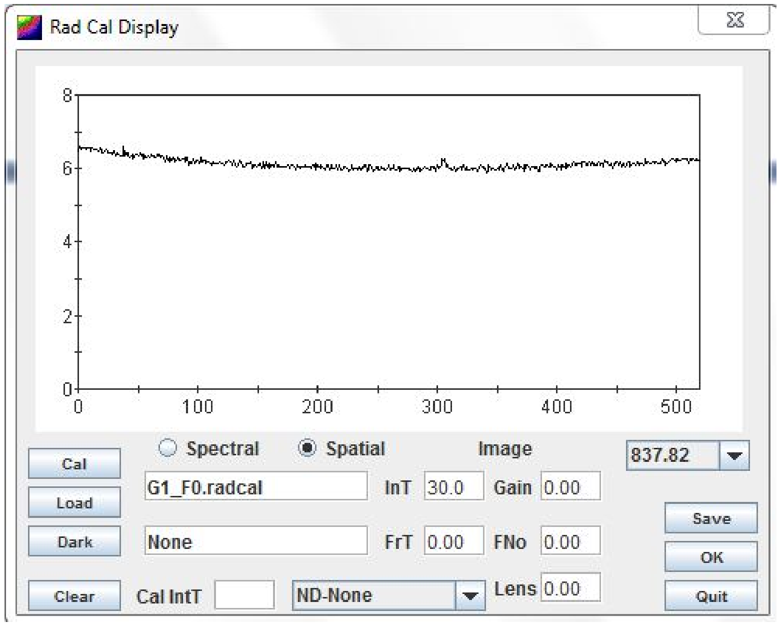

Figure 44: Spatial Gain Calibration Display.

The raw calibration images from the integrating sphere have to be processed first to produce a gain array that can be applied to the data. This is accomplished using the various command buttons, text and combo boxes in the *Rad Cal Display* window.

The *Dark* button reads in the dark image to compute the offsets for the calibration image. The dark image for the calibration data must be read as the first step in preparing the calibration gain array.

The *Load* button reads in the raw calibration image. Both the integration time for the calibration data (*Cal InT*) and the integration time for the image data (*InT*) must be specified first so the proper radiometric correction can be applied. The *Save* button saves the calibration gain array to a file for subsequent application to image data.

Generally, the intensity of the integrating sphere is high enough to saturate the FPA, even for short integration times, so a neutral density filter must be applied. The neutral density filter introduces its own spectral features into the calibration image and must be removed. This is performed using the Combo Box at the bottom of the window, which selects the appropriate neutral density correction for the data.

Currently, both the LabSphere source function and the neutral density filter correction factors are hard-wired in the code based on the hardware configuration used to collect the calibration data at the factory (Surface Optics Corporation). Modification of these spectral source and filter functions for a different hardware configuration is possible by contacting Surface Optics Corporation. A future version of the code will provide the user with a set of tools to modify this data for different calibration hardware configurations.

7.0 SPECTRAL RADIANCE ANALYSIS (*SRA*) TAB

The final tabbed panel of the SRAnal program provides simplified Spectral Radiance Analysis (*SRA*) calculations. Figure 45 shows this tab for an image taken of the exit port of a calibrated integrating sphere.

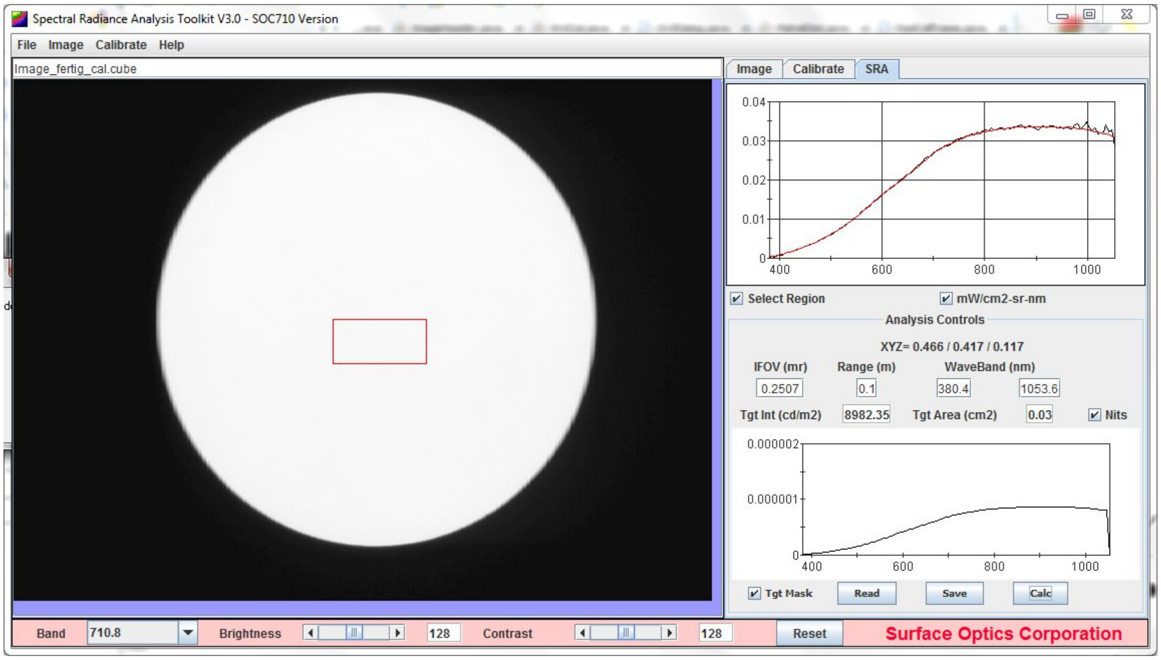

Figure 45: Spectral Radiance Analysis (*SRA*) functions.

The calculation is provided for both radiometric units, Radiant Intensity (W/sr) or photometry units (Candella per square meter, or *nits*) using the *Nits* check box. The spectral plot shows the Spectral Radiant Intensity (W/Sr-nm).

The basis for this calculation requires the definition of a target area, which is computed using the known imager Instantaneous Field of View (*IFOV*) in milliradians for each pixel, the distance from the camera to the target (*Range*) in meters, and the definition of the target pixels. The target is defined using the same *Select Region* tool described in selecting spectral filters. In this case the *Target Mask* check box must be selected as well. Targets can then be *Saved* and *Read* for subsequent processing.

The user can also select a *WaveBand* within the spectral band of the system for the calculation. The *Calc* button then performs the calculation. The *XYZ* again displays the calculation of the tristimulus coordinates for the radiance or defined illuminant (using reflectance units), as was described earlier, and averaged over the area defined by the target mask.

NOTES