camSPECS

User Manual

29. April 2020

Image Engineering GmbH & Co. KG · Im Gleisdreieck 5 . 50169 Kerpen-Horrem . Germany

T +49 2234 2273 99 99 1-0 . F +49 2234 2273 99 99 1-10 . www.image-engineering.com

CONTENT

1 INTRODUCTION

Important information: Read the manual carefully before using the device.

Inappropriate utilization may cause damage to the device, to the DUT (device under test), and/or other components of your setup.

Keep these instructions in a safe place and pass them on to any future user.

1.1 Intended use

camSPECS consists of an illuminating hardware device and software for evaluating the spectral sensitivity of camera systems. The included calibration spectrometer is used for periodic on-site calibration.
The camSPECS software measures spectral sensitivity by capturing images of the filter plate taken with a camera system.

- Only suitable for indoor use.
- Place the system in a dry, constant tempered environment without light interference and avoid high humidity.

1.1.1 Departing from described setup

For commissioning, the following steps must be performed in the correct order. Departing from this order may lead to incorrect results.

- Install the Matlab component runtime (MCR)
- Install the camSPECS software

1.2 General safety information

The backside housing of camSPECS gets hot during operation.

- **Do not** cover the fan discharge ducts on the right and back sides of the device.
- **Place** the back side of the device at a **suitable distance from the walls**.
- **Do not** open the top sliding port of the housing during operation for bulb exchange.
- **Do not** open the device when connected to the power supply.

2 GETTING STARTED

2.1 Scope of delivery

- camSPECS filter box
- Software
- Calibration file
- One replacement bulb
- Calibration device

2.2 Commissioning

- Remove the packaging material.
- The plug for the power supply and the main switch is on the box's backside. Connect camSPECS with a power socket and switch it on.

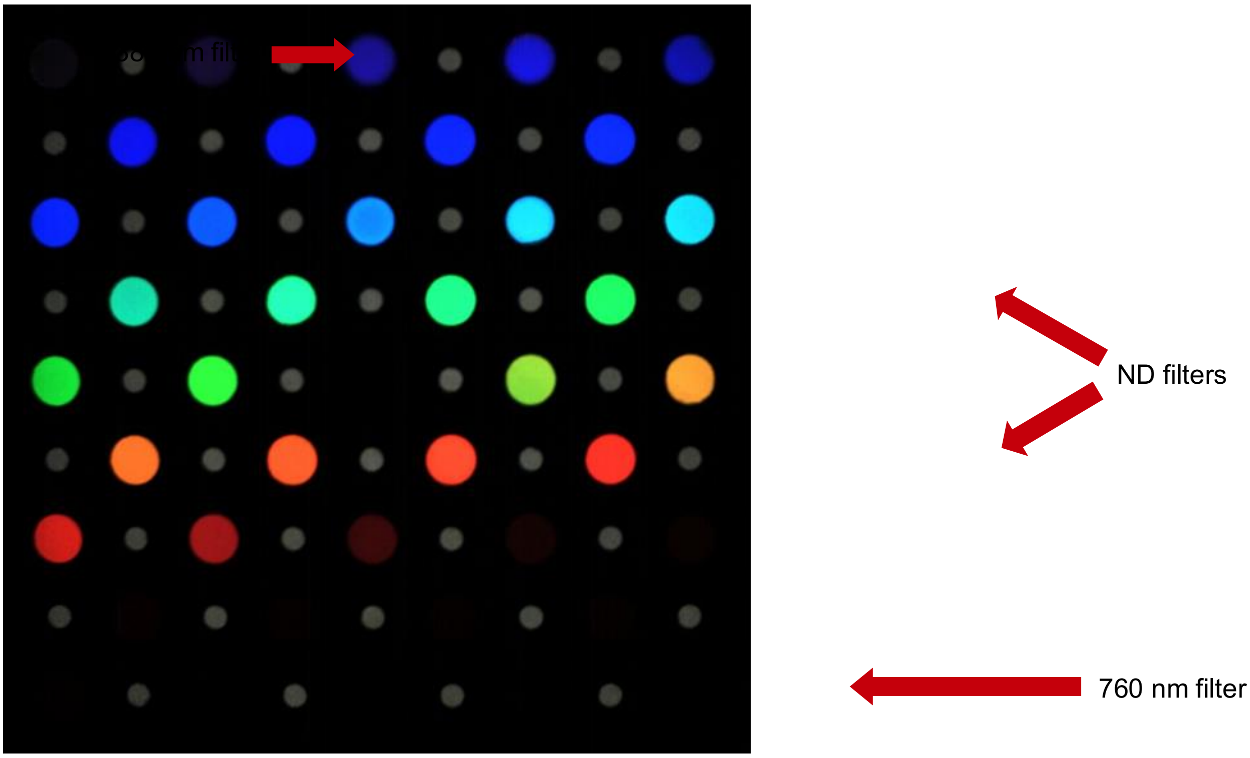
3 OPERATING INSTRUCTIONS HARDWARE

3.1 camSPECS

Switch camSPECS on and let it run for a couple of minutes (>= 4 min) until it reaches a stable temperature.

3.2 Filter panel

A set of 39 interference filters is used to generate narrow-band light. The filters cover a range of 380 - 760 nm in 10 nm steps. The filters are mounted on the front plate of the camSPECS box. The arrangement of the filters can be seen in the following figure. The series starts with 380 nm on the upper left side and continues line by line to 760 nm. The neutral density (ND) filters for inhomogeneity correction are positioned in between.



3.3 Spectrometer calibration

The calibration device for the filters is already calibrated when delivered. The device needs a recalibration once a year, regardless of the operating hours. Please read chapter 5.1.

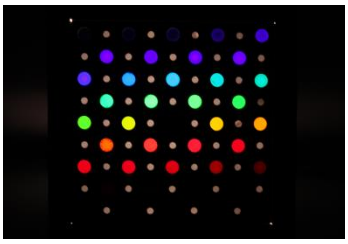
3.4 Camera settings

Requirements on the camera (device under test, DUT):

Set the camera to manual exposure mode. If manual mode is not available, use the automatic exposure mode. The camera should be able to save pictures as linear raw files to get the best results.

Exposure program	Manual
Aperture	No default value
ISO Speed	Lowest value (e.g.100)
Auto focus	Off
File type	RAW

3.4.1 Camera position and lenses used



Place the camera in front of the filter plate. The principal axis of the lens must be aligned perpendicular to the center of the filter plate. Adjust the distance between the lens and filter plate, so the filter plate occupies approximately two-thirds of the field of view of the camera, centered. Avoid using wide-angle lenses since there is a slight angle dependence of the radiance power and the peak wavelength of the interference filters. Using lenses with higher focal distances ensures a minimum viewing angle. Viewing angles below 15° do not cause noticeable impacts on the resulting spectral responses.

Note:

Ensure that the filters are the only light sources captured by the camera. The pictures should be taken in a dark room, or the space between the camera and the camSPECS box should be shielded to avoid stray light or other light hitting the camera sensor.

3.4.2 Exposure

Set camera exposure, so the maximum recorded value of the camera capture of the filter plate is approximately 75% of the valid encoding range. For instance, if the available encoding range is 16 bits per channel and the valid encoding range of the image data is 12 bits per channel, set the exposure so that the maximum value of the recorded filter plate is approximately 3000. To get correct results, the image of the filters must not be overexposed. Take a picture with appropriate exposure settings (typically f = 5.6, t = 1/2s, ISO 100, depending on camera and lens) in RAW mode (with Bayer pattern). Check the RAW image for the highest recorded value in all RGB channels using a RAW image viewer or converter (i.e., dcraw).

4 OPERATING INSTRUCTIONS SOFTWARE

The camSPECS software is a powerful tool to measure the spectral sensitivity of camera systems. The results may be used for comparison or documentation purposes and for calculating Color Correction Matrices (CCM) and ICC profiles.

The results can be saved in plain text (.txt) or XML files. For fast documentation purposes, the resulting plots and images can be saved to images (JPEG, PNG, TIFF, BMP, GIF).

The software allows for a validation of the measurement setup with well-known reference data (based on ColorChecker charts) and a recalibration of the hardware with the included spectrometer.

The camSPECS software also determines the white balancing multipliers of the camera and computes various colorimetric transform profiles.

4.1 To install camSPECS software

- First, install the *Matlab Component Runtime* required for camSPECS. Execute the MCR installer (32 or 64-bit) and follow the instructions. This installer will install the *Matlab Component Runtime* if necessary.
- Then start *camspecs_Vx.x.x_win64.exe* or *camspecs_Vx.x.x_win32.exe* (depending on the Windows operating system version) to install the camSPECS software.

4.2 RAW file conversion

camSPECS uses *dcraw* to convert typical camera raw images to TIFF images. There is a list of all supported cameras at: www.cybercom.net/~dcoffin/dcraw/

Standard processing converts to linear TIFF files while retaining the CFA pattern. A dark frame subtraction (DFS) is supported to suppress fixed pattern noise. Other supported file types are TIFF, BMP, PGM, PPM, and PNG. *dcraw* can also read the EXIF data from the images, such as shutter speed, f-stop, and ISO speed.

4.3 Workflow

This chapter describes the general workflow of spectral response measurement and evaluation.

4.3.1 Spectral sensitivity (camSPECS) module

- Start the camSPECS software and switch to the module *Spectral sensitivity (camSPECS).*
- Check the advanced settings menu to adjust the default values as needed.
- Add the master calibration file delivered on the CD in the settings panel with the "+"-button. More files can be added or removed from the menu using the corresponding buttons ("+," "-"). Calibration files created during the calibration process with the software are automatically added to this menu.
- Update all other settings as needed and add an optional dark image.
- Select and add images with the '+' button.

- Click the *Start* button.
- Check the result of the automatic detection and confirm by double-clicking on the image outside the displayed Regions of Interest (ROI). The rectangles may be rearranged here if necessary.
- The measurement result is displayed, and a text file with the image name is saved in the same directory as the images.
- The spectral curves can be saved as an image file for documentation purposes.

4.3.2 Spectral sensitivity (iQ-LED) module

- Start the camSPECS software and switch to module *Spectral sensitivity (iQ-LED).*
- Select the *Spectral Sensitivity Database*.
- Select the module *Dark frame subtraction* and the image file for an optional dark image.
- Select *Add Spectra Folder* containing the iQ-LED spectral power distribution files, ensuring that the file naming convention is as specified below.
- Select *Add Image Folder* containing the camera captures of the iQ-LED spectra files, ensuring that the file naming convention is as specified below.
- Click the *Start* button.
- The computed spectral sensitivities are displayed and saved as a text file.

4.3.3 Validation module

- Take a picture of a ColorChecker (24 patches) or ColorChecker SG (140 patches) chart that was illuminated by a light source whose spectral distribution is included in the software (D50, D55, D65, A, C). Additional spectral distribution files can be added to camSPECS.
- The picture shall have uncompressed RGB or raw data (e.g., TIFF format).
- Select the *Validation* module and choose a spectral sensitivity measurement. The previous spectral measurement, if available, is shown in the highlighted field.
- Select the light source and reflectance data from the drop-down menus corresponding to the selected ColorChecker.
- Select the ColorChecker image.
- Select a dark image for correction as an option.
- Click the *Start* button and draw a rectangle around the patches in the displayed image.
- Double-click on the image and check the positions of the ROIs in the next step. Their positions may be corrected with drag and drop before clicking on the image outside the ROIs to continue.
- The graph displays the measured RGB values for each patch plotted against the predicted values in normalized values (from 0...1).
- The graph can be saved as an image file for documentation purposes.

4.3.4 Color transforms module

- Select the measured Camera Spectral Sensitivities file.
- Select the Transform type, Reference illuminant, and Profile type.

- Select the training data that will be used to create the transform, the test data that will be used to evaluate the transform, and additional test data (if any) that will also be used to evaluate the transform.
- Click *Start* to calculate the transform.
- Click *Export* to save the transform, if desired.

4.3.5 ICC profile evaluation module

- Load a raw camera image.
- Click *Select ICC profile directory…* to show a list of profiles saved from the *Color Transforms* module.
- The color-managed image will be shown for viewing on an sRGB-calibrated display.
- Export the color-managed image if desired.

4.3.6 Sample data set description

There is a set of sample data available on the USB drive. The images and text files can be used in all modules to gain quick insight into the software. Explanation of the sample data:

- Spectral Sensitivity (camSPECS) module, camSPECS XL folder:
    - XL_Calibration.txt – sample input calibration file for the camSPECS image. Not applicable for customer's hardware.
    - camspecs.ARW– sample input raw capture of camSPECS filter plate.
    - camspecs_*.* – computed output spectral sensitivities saved in several formats.
- Spectral Sensitivity (iQ-LED) module, iqLED folder:
    - SS_RGB.txt – sample input spectral sensitivity database.
    - Image folder - sample input folder of camera captures of the LEDs corresponding to the contents of the Spectra folder.
    - Spectra folder - sample input folder of LED spectra saved from separate iQ-LED software.
    - iQLED_specs.txt – sample computed spectral sensitivities output.
    - cameraPCs.txt, cameraRGBs.txt, LEDspectra.txt, sample output data files.
- Validation module:
    - camspecs_specs.txt – computed spectral sensitivities output from the Spectral Sensitivity module is the input for the Validation module.
    - ColorChecker.RW2 – sample raw capture of Color Checker illuminated with a D65 simulator.
- Color Transforms module:
    - camspecs_specs.txt – computed spectral sensitivities output from the Spectral Sensitivity (camSPECS) module is the Color Transforms profile creation module input.
    - camSPECS.icc - profile created from camspecs_specs.txt
    - iqLED.icc - profile created from iQ-LED_spectral.txt

- Profile evaluation:
  - Test Images folder - sample images to which sample ICC profiles may be applied.

Sample data set is provided with camSPECS for setup and functionality verification. It's recommended to exercise all software functions with this data set to ensure that the illustrated results can be replicated. Sample data set files are used throughout the documentation for illustrative purposes only.

4.4 Image data

The camSPECS software can handle demosaiced images or images with the original CFA independent from the file type. With other raw image converting software, convert the images to TIFF files and maintain the Bayer pattern. The program *dcraw* converts raw camera files (the latest release is delivered with camSPECS). Mac OS X and Windows versions are available. camSPECS can also handle RGB images as long as they have adequate bit depth, have not been rendered for color and tone, and are radiance linear.

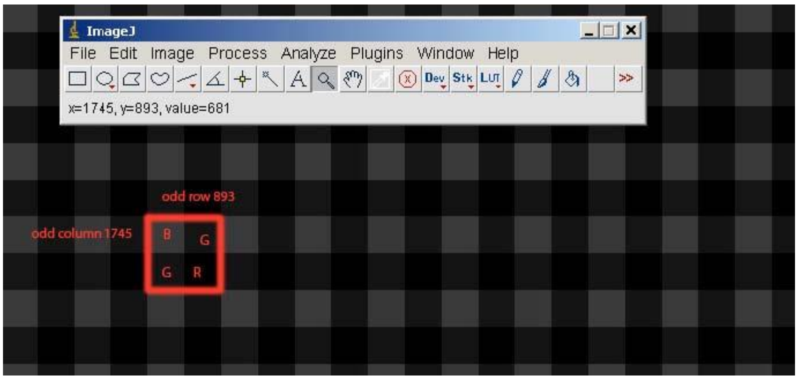
If raw files are selected, the raw processing is performed automatically for all images selected in every module. The files are saved as TIFF files to a sub-directory named "converted" at the location of the original files. These images are used for subsequent processing. If further tests with images are desired, choose the converted images for faster processing. Images are converted, retaining the original Bayer pattern.

Note

See www.cybercom.net/~dcoffin/dcraw/ for a list of all supported cameras. On this site, there is a link to the latest executable version of *dcraw*. To update *dcraw,* replace the *dcraw.exe* with the new one in the "app" directory of the camSPECS program. Or choose *dcraw* from a different location in the advanced settings.

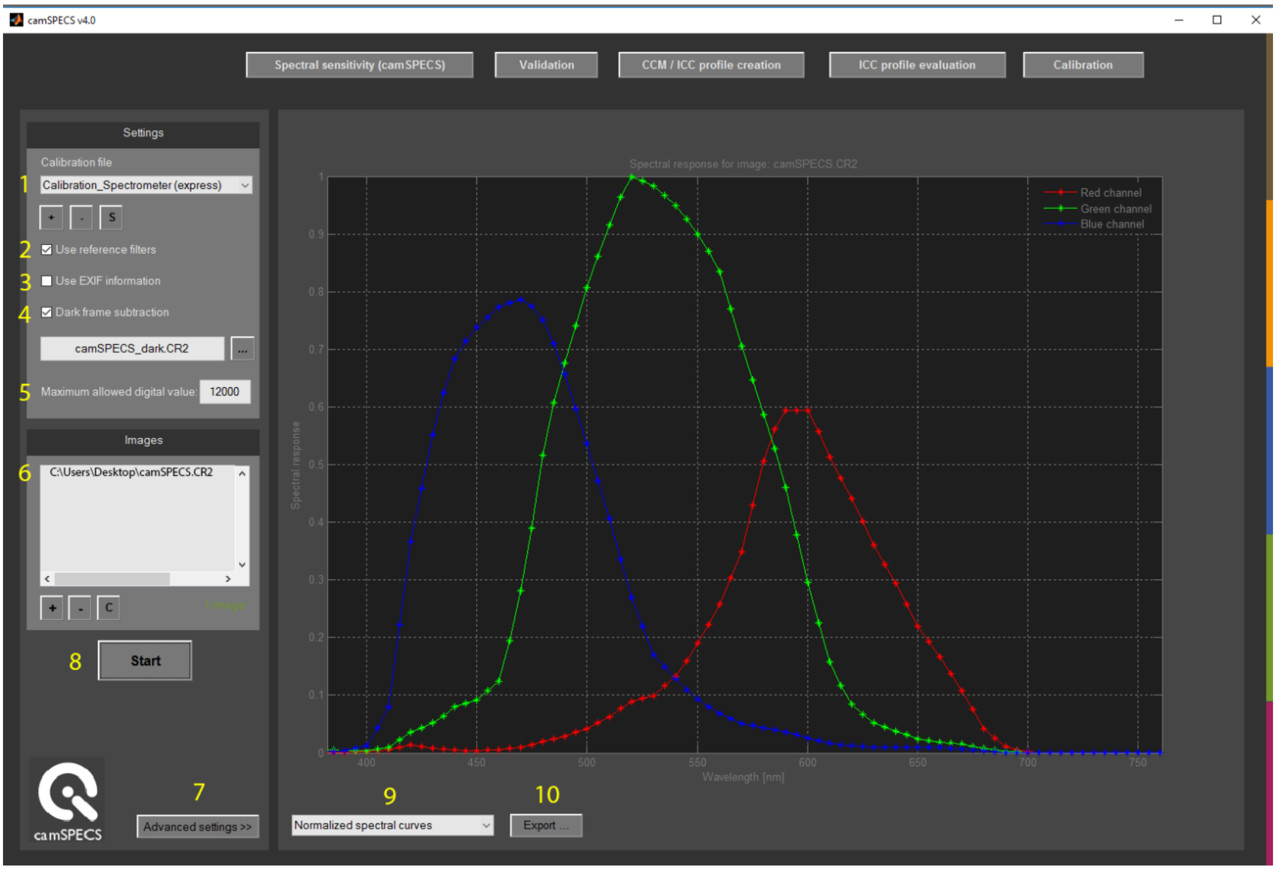
4.4.1 Color filter array (Bayer pattern)

Sometimes it might be necessary to set the CFA manually. To determine how the pixels are located in the CFA, see the corresponding filters in an image taken with camSPECS. These filters represent blue, green, and red. Non-standard color filter arrays are supported: select 'C' (for Clear) for each channel in the corresponding drop-down menu in the advanced settings panel.



For example, in the CFA in the 450 nm picture, the brightest pixel is blue. The brightest pixel in the 650 nm filter picture is red; the remaining two pixels of a 2x2 area represent the green channel of the camera. This procedure should work with most regular 3-channel cameras.

4.5 Spectral sensitivity (camSPECS) module



Description of the numbered controls marked in the image above:

1. Select the calibration file for the camSPECS hardware. Calibration files can be added and removed from the list using the '+' and '-' buttons. The' S' button can save all calibration files to a specified location. The selected calibration file in the menu must correspond to the images selected. The calibration files are located in the directory /calibration_files/filter of the camSPECS program folder.

Wavelength (nm) of the color filters or ‘1’ for the ND filters	Power of the filters
377	0.1933
1	0.1009
386	0.1629
1	0.1219
...	...
750	0.0829
1	0.1681
760	0.0604
1	0.1094

The table above explains the formatting of the calibration file for camSPECS V2: the rows contain values for the wavelength and the power of the color filters and the ND filters alternating from line to line. “1” stands for the ND filter.

2. The ND filters adjacent to the interference filters are used for correcting inhomogeneities caused by the DUT (camera + lens). This option should always be selected.
3. Use EXIF data for correction of different exposure settings. This option is only necessary when the camera's automatic exposure control is used in the Multi-shot version of camSPECS.
4. Apply dark frame subtraction. Supported image types include TIFF, PGM, BMP, PNG, PPM, and raw files. Take an image with the same camera exposure settings used for the camSPECS images. It will be subtracted from each image in the processing list. This option subtracts the offset value of all images originating in the sensor's dark current. The offset value hurts the spectral measurement.
5. Set the maximum allowed digital value per the Exposure guidelines above. An error message is displayed if this value is exceeded in an image.
6. Add an image(s) to the processing list. Supported image types include TIFF, PGM, BMP, PNG, PPM, and raw files (The term "raw file" indicates files that are created by a digital camera in "RAW-Mode" and are readable by the software *dcraw*. This term does not include raw files with unsupported image file formats – these should be converted to 16-bit Tiff images first.). Depending on the selected calibration file (see item 1), one or more images can be chosen that contain the filter arrangement of camSPECS. The '+,' '-,' and 'C' buttons are options to add images, remove one selected image or clear the whole list. After the measurement, the spectral curve of the first image in the list is displayed. The corresponding results are displayed by clicking on the other images in the list.
7. Check the advanced settings (chapter 0).
8. Starts the processing procedure. The filters in the images are detected automatically or manually. After the detection process, a confirm dialog is shown where the ROIs for each filter can be manually repositioned if necessary (Fig. 4.5.2). Double-clicking on the background starts the processing. The resulting spectral curves are displayed and saved to plain text (*specs.txt or *QE.txt) and an XML file in the same directory as the original image directory. If multiple images are selected, an additional *_SS.txt file is created and saved in the installation camSPECS/lib folder, which is the default location when selecting the Spectral Sensitivity Database in the Spectral sensitivity (iQ-LED) module. For the camSPECS version (Multi-shot), a tile image is saved to the same directory as the origin of the image's directory (Fig. 4.5.1), assembled from all images. Check this image for the correct positions of the ROIs or all filters.
9. When the measurement is done, switch between raw and normalized RGB spectral curves data. *Raw spectral curves – single* plot the uncorrected camera code values as a function of wavelength for the highlighted image, while *Normalized spectral curves – single* apply the calibration file from 1 above and then plot the corrected camera code values as a function of wavelength. *Quantum Efficiency* shows the normalized spectral sensitivities converted to quantum efficiencies. Similarly, the * - *all* choices plot the curves for the complete set of images. The order of the legend is the same as the image list. The valid spectral range is specified in the spectrometer_settings.txt file described above.

10. Export the spectral curves to an image (JPEG, PNG, TIFF, BMP, GIF) for documentation purposes.

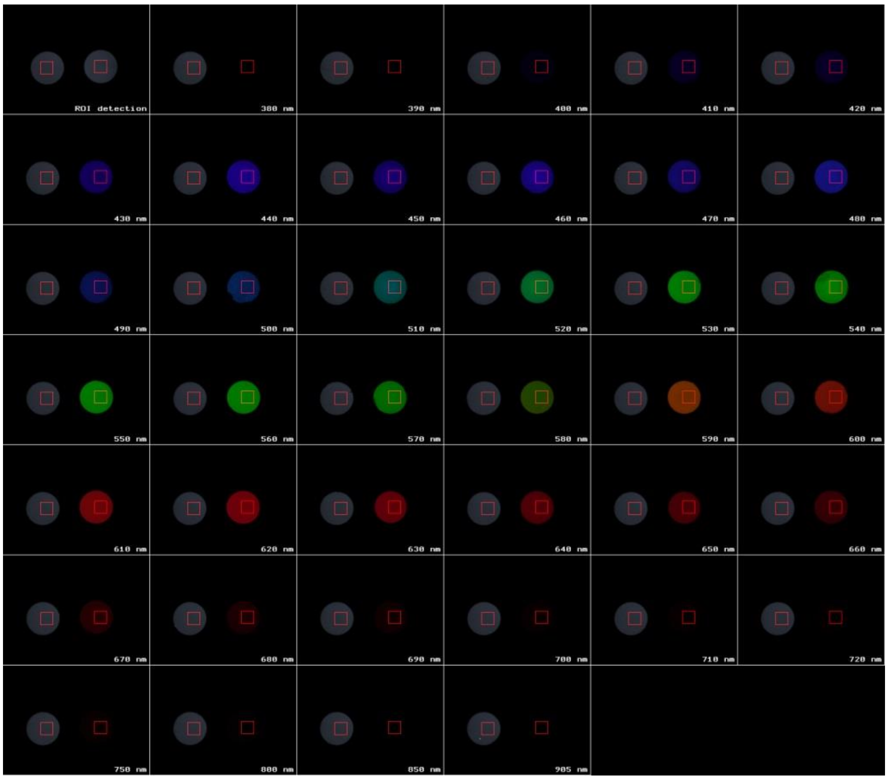


Figure 4.5.1: A tiled image is created from all images of a series for camSPECS multi-shot. Displaced filter frames can easily be identified.

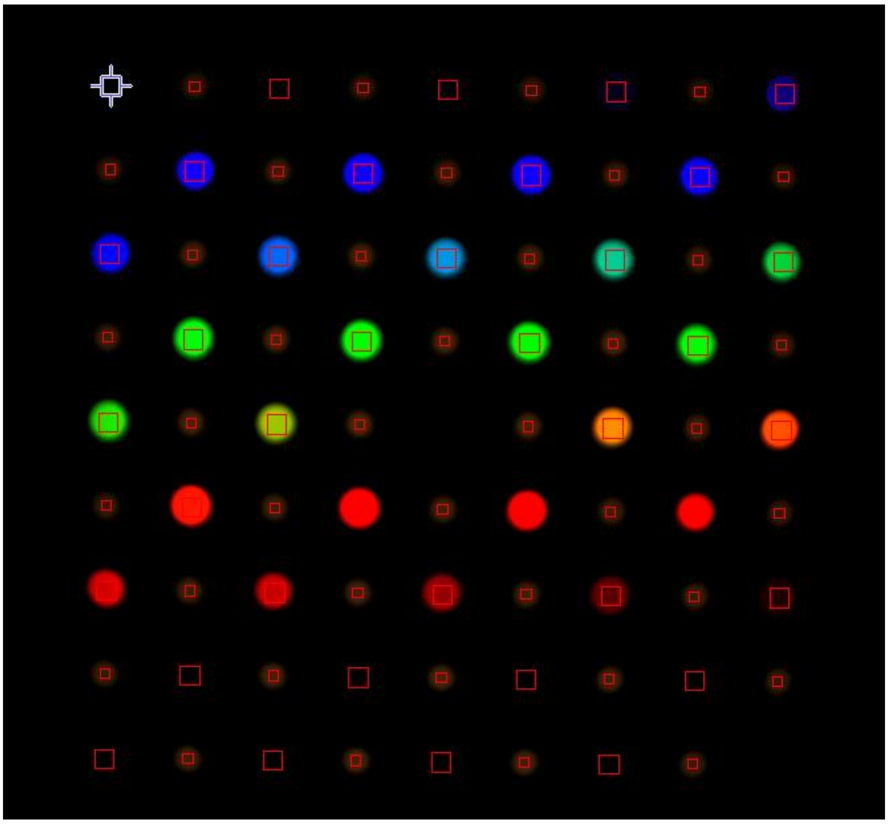
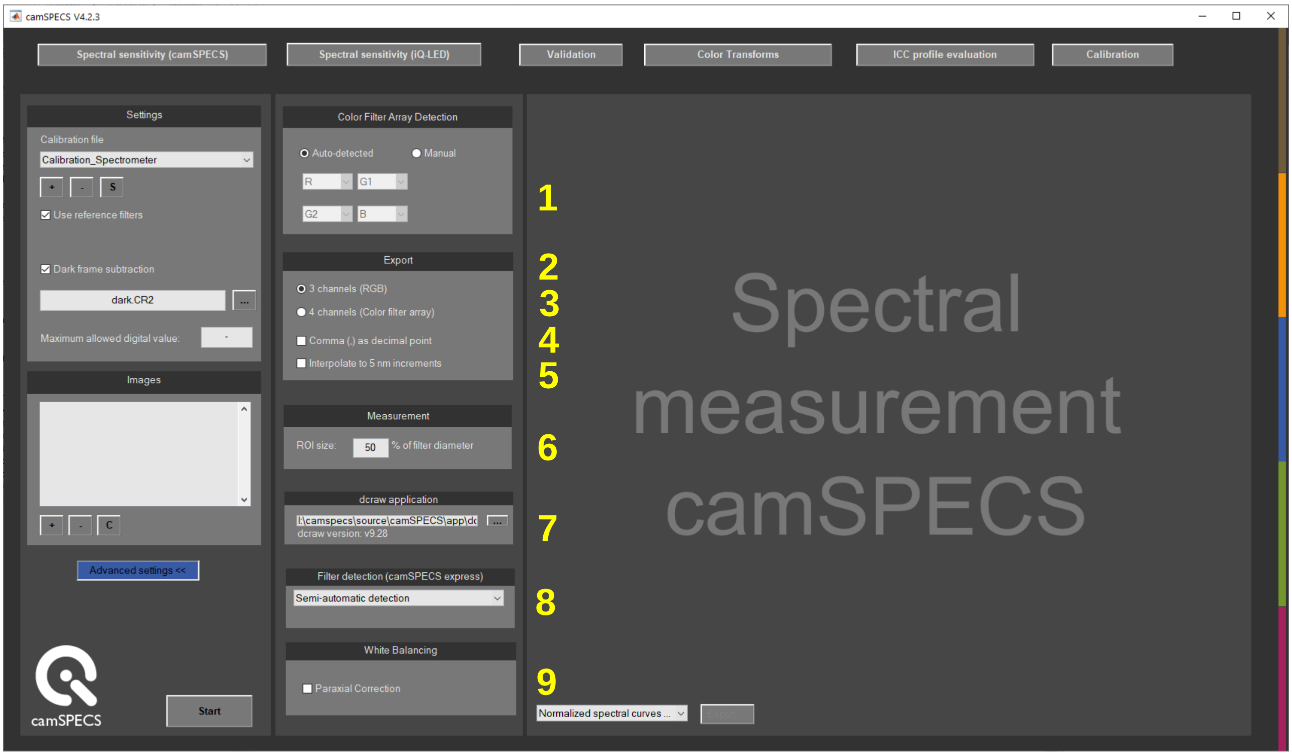


Figure 4.5.2: camSPECS filter capture with adjustable ROIs for modifying measurement areas.

4.5.1 Advanced settings



1. The software detects the Color Filter Array (CFA) automatically by default. Choose the manual option to set the color filter array manually. If a CFA is not a standard pattern, e.g., unique cameras without a filter for one channel, C (Clear) can be chosen. In this case, all four channels are measured separately and displayed as four different channels without any assignment to a color.
2. This option is the default for the display and export of the curves. Both green channels are averaged.
3. With this option, all four channels of the CFA are displayed and exported as result files separately.
4. Use a decimal comma in the resulting text and XML files.
5. This option interpolates the spectral response data to increments of 5 nm. The default value is 10 nm if this option is not selected. 5 nm graded values are necessary for further processing in the modules *Validation* and *CCM calculation*.
6. Size of the ROI for measuring digital values in every filter to the diameter of the filter. The default value is 50 %. Higher values may result in inaccurate results due to vignetting artifacts of the filters near the borders. The minimum size is limited by the number of pixels inside the ROI; more than 100 pixels are needed for statistical significance. If the number falls below this value, the program gives a warning.
7. Select the *dcraw* application (see note below). By default, the *dcraw* version delivered with the software is used and located in the directory "app" inside the camSPECS program directory. For raw image processing, camSPECS uses *dcraw* to convert standard camera raw files to TIFF files, and the converted images are saved to a sub-directory named 'converted.'

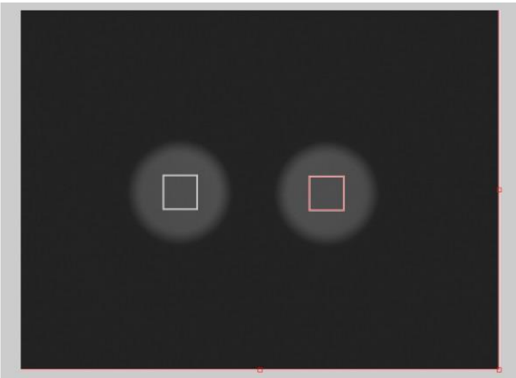
Note:

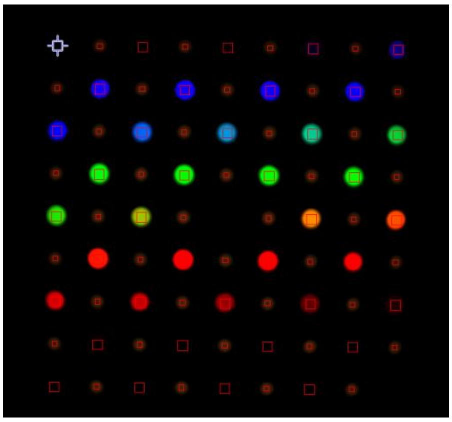
A long file path or a network path can cause problems using *dcraw*. Try to use short paths. (For example: C:\program files\dcraw). See www.cybercom.net/~dcoffin/dcraw/ for a list of all supported cameras and the current version of *dcraw*.

8. Choose the detection mode for the filters in camSPECS images:

   - *Automatic detection*: Several camSPECS images can be measured subsequently without interruption.

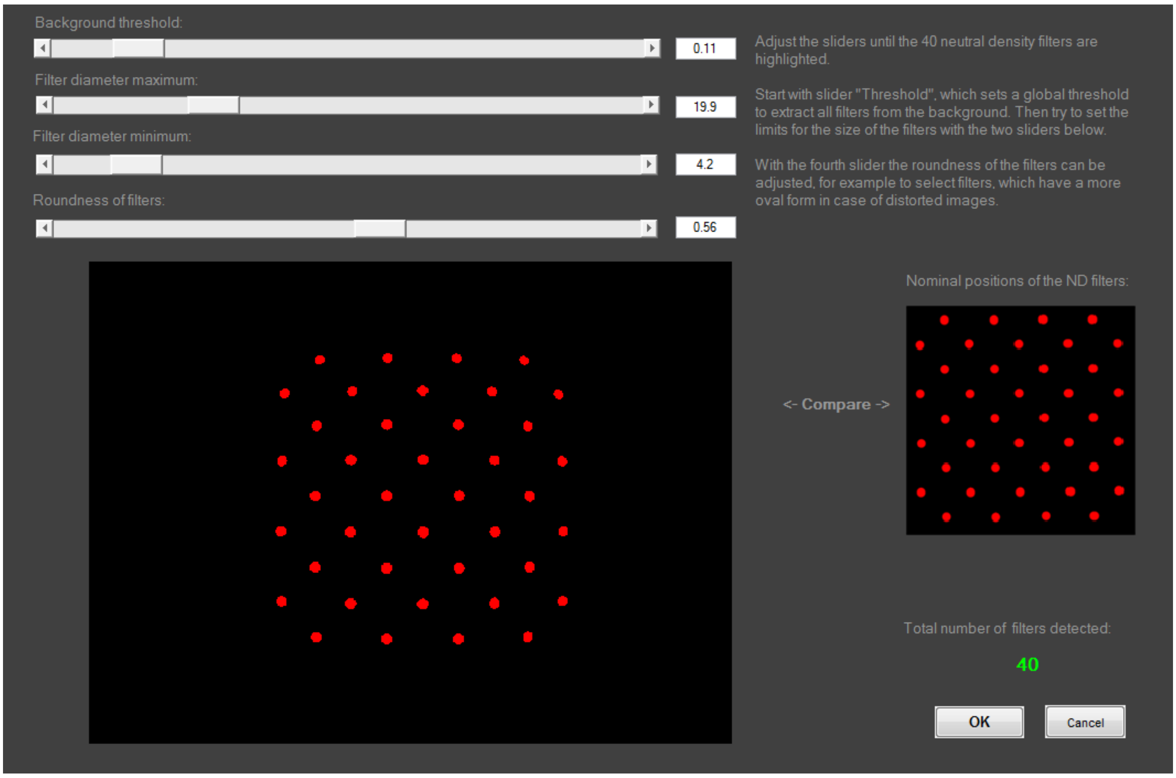
   - *Semi-automatic detection:* Each spectral measurement is interrupted by a dialog to control the filters' ROI locations. The preceding filter detection is automatic, and the ROIs can be activated and aligned with the mouse.





Semi-automatic detection of the filters in camSPECS. The ROIs shown in this example were set to a size of 50% (left), respectively 70% (right) of the diameter of the corresponding filters.

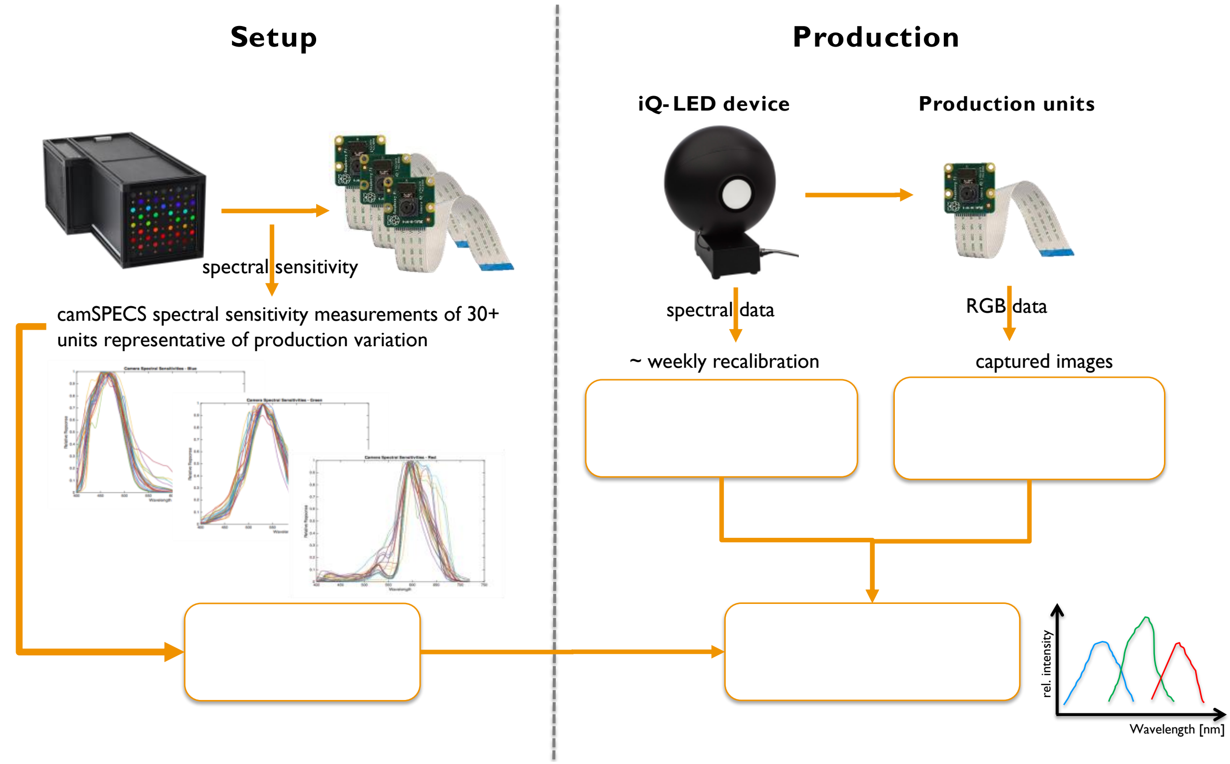
   - *Manual detection*: Each spectral measurement is interrupted by a dialog for manual detection of the filters. Use this option if the automatic detection fails. Reasons for failing are mostly images exposed with wide-angle lenses or images with artifacts caused by stray light during shooting. Use the four sliders to limit the characteristics of the neutral density filters. Compare the detection in the image (left side) to the nominal positions of the filters. If the correct number of filters of 40 is found, continue by clicking the *OK* button. This dialog panel is also invoked when automatic detection fails with an image.



9. Check White Balancing Paraxial Correction when characterizing cameras with wide-angle lenses or when matching white balance over a wide range of focal lengths is desired.

4.6 Spectral sensitivity (iQ-LED)

The Spectral sensitivity (iQ-LED) module is intended to help identify the parameters for high-speed production-line camera colorimetric calibration using Image Engineering illumination devices that embed iQ-LED technology. While the Spectral sensitivity (camSPECS) module directly determines a camera's spectral sensitivities, the Spectral sensitivity (iQ-LED) module determines the spectral sensitivities of production-line cameras. Images captured from a few LEDs combined with an analysis of a database of reference spectral sensitivities from cameras with the same make and model sampled from production. The database is created with a monochromator such as camSPECS then data from a test camera is selected for parameter optimization and comparison of results as described below. This process can be repeated for additional test cameras to confirm that the optimized parameters are robust across the cameras under test.



The method is comprised of two parts, as illustrated above, assuming the use of camSPECS software v4.2, camSPECS monochromator, iQ-LED software v3.3, and an iQ-LEDV2-based instrument:

Setup is a do-once operation wherein a set of camera modules of a given make and model are selected that represent production variation. Each module is measured with a monochromator (such as camSPECS, as described in the previous section) to determine spectral sensitivity. This process is repeated for each module in the set resulting in a spectral sensitivity camera database that characterizes the statistics of spectral variation of the given make and model. **Setup** is performed for each make and model of the camera module resulting in a unique spectral sensitivity camera database for each make and model of a camera module. **Setup** best practices are comprised of the following steps Spectral Sensitivity Database Creation, iQ-LED Settings, and Verification.

Spectral Sensitivity Database Creation:

1. Select 43 camera modules that are representative of the expected production variation.
2. Select one of the camera modules to optimize the exposure of the camSPECS filter plate, allowing for adequate headroom. Capture a black frame with these settings.
3. Select 43 camera modules and make captures with these settings of the camSPECS filter plate.
4. Select 40 of the 43 camera modules. The remaining three modules will be used later for Verification. Create the representative spectral sensitivity database by loading the black frame and all 40 captures of the camSPECS filter plate in the **Images** section of the Spectral sensitivity (camSPECS) module. After selecting **Start**, each module's spectral sensitivity will be displayed and should be inspected for expected behavior. Once all 40 modules have been processed, the new representative spectral sensitivity database is written to Program Files > Image Engineering > camSPECS > lib.

iQ-LED Settings:

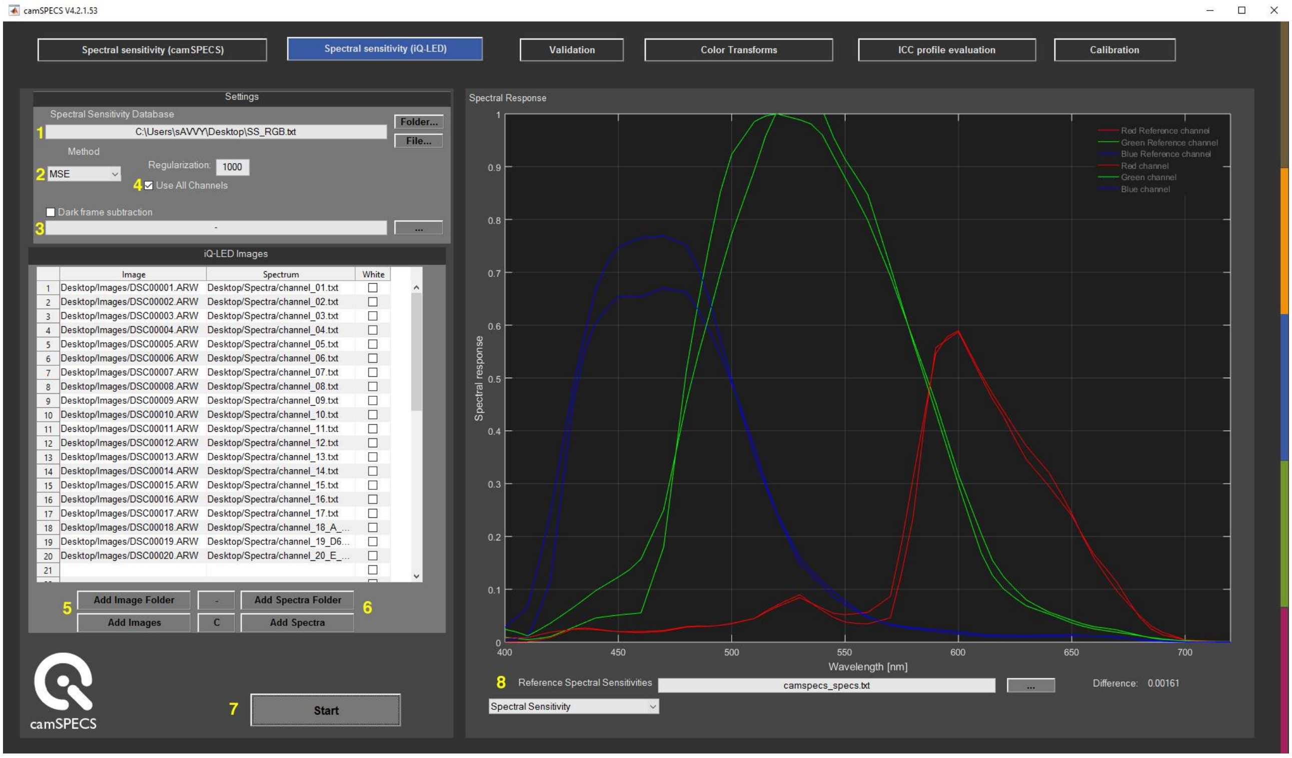
1. Since the spectral sensitivity of typical modules has been measured above, the spectral sensitivity wavelength range is known. Once an iQ-LED V2 device and spectrometer are connected to the computer, launch the iQ-LED software v3.3 and allow for warmup.
2. Select the first LED (blue) for which the camera has sensitivity. Set its power to 95% with all other LEDs set to 0 and drag the **Current Illuminant** to the **Stored Illuminant** panel. Repeat for only those LEDs for which the camera has sensitivity resulting in a series of individual LED stored illuminants at 95/0% power over only the camera spectral sensitivity wavelength range. Do not include LEDs whose peak output lies outside the camera spectral sensitivity wavelength range.
3. Since the stored illuminants are the reference for these LEDs, use the **Stored Illuminant** panel to select the just created stored illuminants. With a mouse-right-click, select **Export selected illuminant(s) reference spectra** to a new folder.
4. Within **Create Illuminant, 1) select spectral distribution A** and **2) select intensity** corresponding to 95% of maximum **Illuminance [lx]** shown after selecting circle **i**. Drag the **Current Illuminant** to the **Stored Illuminant** panel. The **spectral measurement** panel will show the reference illuminant and the created spectrum. Since the reference and actual spectra are not the same, use the **File Save** icon in the upper left of the measurement panel to save the measured spectrum. Repeat for **Illuminants D65** and **E**. Confirm that the red triangle with "!" is not displayed.
5. Rename all the saved stored illuminant text files in the folder to follow the naming convention (text_number) and order (short to long wavelengths, A, D65, E) illustrated in column A of the spreadsheet below.
6. When the camera module is placed directly at the exit port of the iQ-LED device and all ambient light is excluded, perform captures of each stored illuminant in the order above and with exposure set for adequate headroom for the brightest illuminant. Save these images using the naming convention text_number.ext so that the numbering order is the same as the capture order specified.
7. Launch the camSPECS software Spectral sensitivity (iQ-LED) module and load the dark frame, image folder, and spectra folder as described below. With the default settings, click **Start,** and after completion, open the cameraRGBs.txt file output in the images folder, illustrated in columns C:E below.
8. Inspect to ensure that these values do not exceed 75% of the valid linear encoding range, including any black offset associated with the dark frame. Inspect the maximum values illustrated in column F below to ensure that the maximum camera response to each stored illuminant is approximately balanced.
9. The maximum camera response to each stored illuminant should be approximately balanced to achieve proper neutral balance in subsequent spectral sensitivity determination reliably. The estimated adjusted powers will create approximate balance as illustrated in column H. Create a new set of stored illuminants with these powers (minimum 15%), increase exposure proportionately, and repeat steps 5-8 above. Confirm that the maximum camera response to each newly adjusted stored illuminant is approximately balanced, as illustrated in columns I:L.
10. The existing stored illuminants must be deleted and recreated anytime an iQ-LED device is recalibrated.

A	B	C	D	E	F	G	H	I	J	K	L
ILLUMINANT	POWER	R	G	B	MAXIMUM		POWER	R	G	B	MAXIMUM
Ch_01.txt	95	6.094968013	15.23591695	67.35735547	67.3573555		95	45.99527603	114.0931799	490.969894	490.969894
Ch_02.txt	95	17.19291257	50.94639631	225.0067528	225.006753		95	129.2257952	381.147698	1675.536392	1675.536392
Ch_03.txt	95	21.140364	95.83825228	366.4892637	366.489264		76	117.6854638	521.8829597	2016.325931	2016.325931
Ch_04.txt	95	27.82927082	224.0458476	563.2009611	563.200961		49	108.9969568	863.852887	2195.284763	2195.284763
Ch_05.txt	95	55.25231756	567.2341473	903.6522554	903.652255		30	133.1060375	1365.753128	2199.761129	2199.761129
Ch_06.txt	95	23.15518007	260.3831374	137.5262706	260.383137		95	178.1211053	1995.178359	1060.800594	1995.178359
Ch_07.txt	95	466.6356178	1575.208221	437.2292308	1575.20822		17	688.7177393	2292.660596	604.3275456	2292.660596
Ch_08.txt	95	9.442734866	29.82999645	1.528780654	29.8299964		95	73.24132212	235.9658512	12.04261195	235.9658512
Ch_09.txt	95	221.5373771	146.0138165	8.793019192	221.537377		95	1773.498038	1184.868806	72.3729564	1773.498038
Ch_10.txt	95	320.1882701	155.8908157	11.24216621	320.18827		87	2394.386292	1186.942853	85.65051534	2394.386292
Ch_11.txt	95	264.2664969	64.62537762	10.0927171	264.266497		95	2035.773627	496.5257116	78.38861657	2035.773627
Ch_12.txt	95	357.5850018	76.60437892	15.99614234	357.585002		78	2302.29584	492.1543508	102.3490256	2302.29584
Ch_13.txt	95	245.8278714	45.44470442	16.53371194	245.827871		95	1873.167331	348.2066254	127.0879783	1873.167331
Ch_14.txt	95	125.9856948	27.44714415	10.56712031	125.985695		95	977.9448007	213.3929518	82.85469731	977.9448007
Ch_15.txt	95	22.66739723	6.125692305	2.218153951	22.6673972		95	179.9650515	48.11156853	17.13916449	179.9650515
Ch_16_A.txt	95	1061.275389	1557.033005	531.969931	1557.033		15	1236.749415	1835.543919	614.8923854	1835.543919
Ch_17_D65.txt	95	714.9769207	1880.171133	1116.336223	1880.17113		15	876.7450909	2276.048406	1339.254805	2276.048406
Ch_18_E.txt	95	778.9338423	1808.5992	1024.125881	1808.5992		15	938.1873963	2189.667941	1241.910148	2189.667941
Maximum		1061.275389	1880.171133	1116.336223	1880.17113			2394.386292	2292.660596	2199.761129	2394.386292
Minimum		6.094968013	6.125692305	1.528780654	22.6673972			45.99527603	48.11156853	12.04261195	179.9650515
Ratio		174.123209	306.9320232	730.2134682				52.05722192	47.65300044	182.6647854	

Verification:

1. Please select one of the remaining three camera modules and measure its spectral sensitivity.
2. This module captures the iQ-LED device using the adjusted stored illuminants, as seen above.
3. Launch the camSPECS software Spectral sensitivity (iQ-LED) module. Load the custom spectral sensitivity database, the dark frame for this camera module, the image and spectra folders corresponding to the adjusted stored illuminants, and with the default settings, click **Start**.
4. Load the **Reference Spectral Sensitivities** for this camera module from 1 above.
5. Optimize the settings described below to minimize the difference between the computed and **Reference Spectral Sensitivities**.
6. Confirm these settings by repeating 1-5 above with the remaining two camera modules.
7. In **Production**, each camera module on the production line is presented to an iQ-LED device and individually captures a series of LEDs. The iQ-LED spectral data are combined with the corresponding camera module RGB data and the spectral sensitivity camera database to compute the spectral sensitivity of the production-line camera module.
8. Since the estimation method is susceptible to the particular spectral characteristics of a given make and model of a camera module, the set of optimal estimation parameters should be determined through the default settings. It usually gives a reasonable, if not optimal, result or starting point. Once the optimum set of parameters has been identified, they may also be implemented directly in the production-line calibration API (available from Image Engineering). A default database created from more than 40 camera makes and models is provided with the sample data set purely for illustrative purposes. The features described below may be exercised with data from another camera, make, and model. This data set is shown with the default (not optimized) settings. For actual production-line camera color calibration,

this database must be replaced with a database of reference spectral sensitivities from cameras of the same make and model sampled from production before parameter optimization.



Description of the numbered items marked in the image above:

1. **Spectral Sensitivity Database** selects the reference spectral sensitivities that are representative of the production cameras whose individual spectral sensitivities are to be determined. It is assumed that a minimum representative sampling of 30 cameras has been measured previously with camSPECS as described in section 4.5 item 8 or another monochromator and that these reference spectral sensitivities have been saved in the correct SS_RGB.txt format. With this new representative spectral sensitivity database selected, the parameters described next can be optimized.
    - To create the database, **Folder** selects all the reference spectral sensitivity data within the selected folder.
    - **File** selects the reference spectral sensitivity database directly and is the recommended selection.
2. The **Method** is a pop-up that offers choices for how the spectral sensitivities of the test camera are computed.
    - The **MSE** (Mean Square Error) is the simplest method and applies in most cases where the variance in the spectral sensitivities database is small and arbitrary constraints are not required. **Regularization** controls the tradeoff between the accuracy and robustness of the results. Use the smallest value that minimizes the **difference** between the computed and the **Reference Spectral Sensitivities** for the set of test cameras.
    - The **PCA** (Principal Component Analysis) method has increased precision when the variance in the

spectral sensitivities database is small and if constraints are required. When this method is selected, the **Smooth Components** checkbox is available to enable regularization, thereby reducing noise artifacts. The **Number of Components** pop-up becomes active and selects the number of principal components extracted from the reference spectral sensitivity database that will be used for computing the spectral sensitivity of the test camera. Use the smallest value that minimizes the **difference** between the computed and the **Reference Spectral Sensitivities** for the set of test cameras.

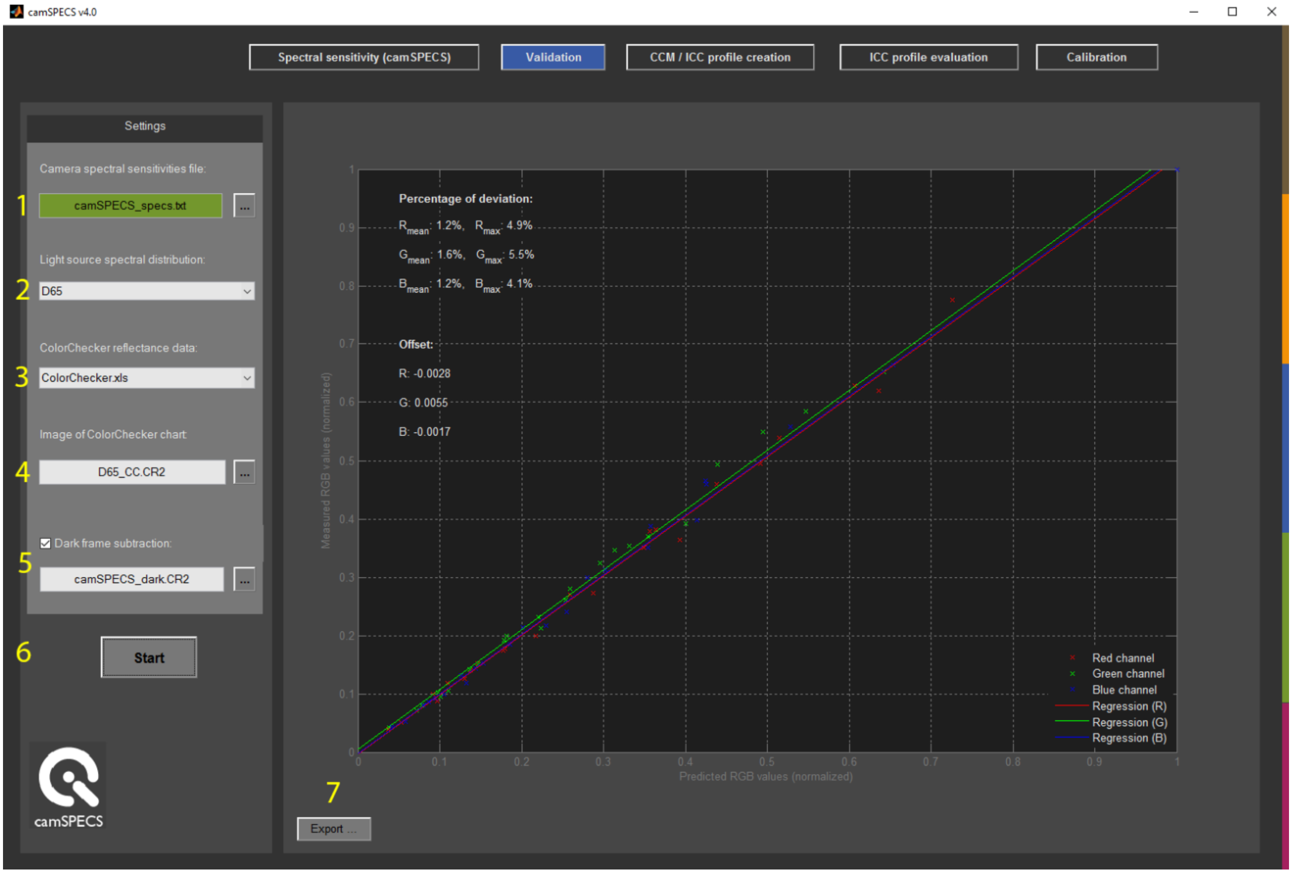
- The **EVA** (Eigenvector Analysis) method applies if the variance in the spectral sensitivity database is significant, if the test camera is significantly different from those in the spectral sensitivity database, and if constraints are required. When this method is selected, the **Smooth Components** checkbox is available to enable regularization, thereby reducing noise artifacts. The **Number of Components** pop-up becomes active and selects the number of eigenvectors extracted from the reference spectral sensitivity database that will be used for computing the spectral sensitivity of the test camera. Use the smallest value that minimizes the **difference** between the computed and the **Reference Spectral Sensitivities** for the set of test cameras.

3. The **Dark Frame Subtraction** checkbox selects a dark capture taken with the camera when the lens cap is on or by another means to ensure no light reaches the image.
4. The **Use All Channels** checkbox determines whether all **Image** and **Spectrum** data is used. This option helps determine the minimum number of measurements required on the production line to achieve a given level of performance. If unchecked, the **Significance** textbox becomes active, and a number between 0 and 1 may be entered. If the relative strength of a given LED channel exceeds **Significance**, its **Image** and **Spectrum** data are used, and the report **LEDstrengths.txt** is written. This strength is specified for each LED channel, and if it is 0 for all three RGB color channels, it does not need to be included in the performance data set. However, using at least 2 LED channels per RGB color channel and at least one white is recommended. Use the smallest value that optimizes the tradeoff between minimizing the number of measurements and the **Difference** between the computed and **Reference Spectral Sensitivities** for the set of test cameras. More measurements ensure greater robustness, while fewer measurements reduce total measurement time.
5. **Add Spectra Folder** selects the folder containing the spectral power distribution files for the desired individual LEDs previously saved using the "Export" feature in the separate iQ-LED software. **Add Spectra** selects individual spectral files rather than an entire folder. **-** removes an individual selection while **C** clears all selections. Each entry in the **Spectrum** list must have a corresponding **Image** entry. Creating several kinds of white illuminants using the "3) create illuminant" function of the separate iQ-LED software is also recommended. The spectral power distributions for the custom white illuminants can be saved from the "spectral measurement" panel in the iQ-LED software. One helpful set of whites to include in the list are A, D65, and E, with illuminant E most beneficial for white balancing the computed spectral sensitivities. The naming convention for the exported and any additional white spectra is illustrated in the **iQ-LED Images** window. If **White** is checked, the corresponding **Image**/**Spectrum** pair will be used to white-balance the computed spectral sensitivities. Illuminant E is recommended for this

purpose.

6. **Add Image Folder** selects the folder containing the image capture files of each spectrum specified in item 5 above. When performing image captures of an iQ-LED device, it is recommended to fill the frame and set the exposure to ensure that the range of the maximum values of the captures uses approximately three-quarters of the allowable encoding range for the camera. **Add Images** selects individual image files rather than an entire folder. **-** removes an individual selection while **C** clears all selections. Each entry in the **Image** list must have a corresponding **Spectrum** entry. The images should be captured in the same order as the **Spectrum** list. The image naming convention is illustrated in the **iQ-LED Images** window and should be of the form alpha description followed by the image number.
7. **Start** initiates the computation of the test camera spectral sensitivities and produces several outputs, including:
   - **iQ-LED…spectral.txt** are the computed spectral sensitivities of the test camera
   - **iQ-LED…quantum.txt** are the computed quantum efficiencies of the test camera
   - **cameraRGBs.txt** are measured camera values for each **Image** and are helpful when checking to ensure that the camera values use the desired encoding range and are not clipped
   - **LEDspectra.txt** are the spectral power distributions for each **Spectrum**
8. The **Results** panel shows several outputs, including:
   - **Reference Spectral Sensitivities** allows entry of the known spectral sensitivities file for the test camera measured with camSPECS. If entered, the **Difference** shows the mean squared error between the computed and the **Reference Spectral Sensitivities**. The parameters described above can be quantitatively optimized by monitoring the difference for the set of test cameras.
   - **Spectral Sensitivity** displays the computed spectral sensitivities for the test camera
   - **Illumination spectra** are the spectral power distributions of the various **Spectrum** samples selected as described above in point 4
   - **Quantum Efficiency** shows the computed quantum efficiencies for the test camera
   - **Images** preview the **Image** selected as described above in point 5 and allow the specification of the **ROI size in a percent**: wherein the region of interest may be selected by either entering a percentage value or by dragging the square itself

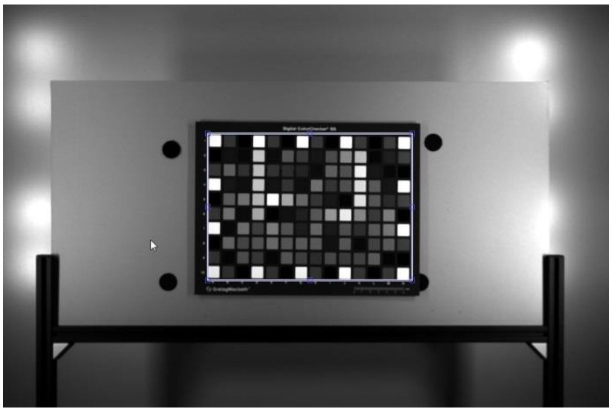
4.7 Validation module

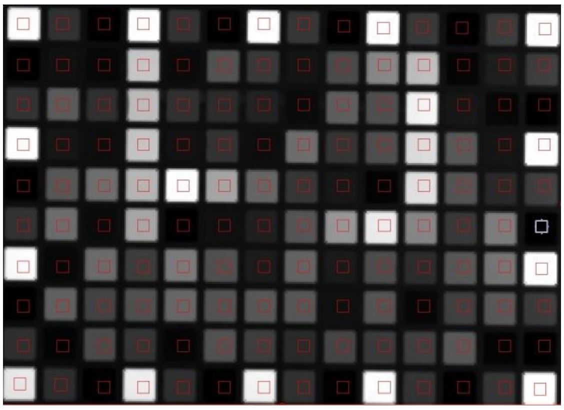


1. Select a spectral response text (.txt) file with values interpolated to 5 nm (see advanced settings) that was exported from the spectral sensitivity module.
2. Select a spectral distribution for the light source used for the illumination of the ColorChecker test chart. Individual light sources may be used here. Intensity values for wavelengths between 380 and 780 nm in 5 nm steps are needed to create an individual light source file. Put this data into a text file with the wavelength values in the first column and the intensity values in the second column. Columns must be separated with a tabulator. The files in the /calibration_files/light source directory of the camSPECS program folder may be used as a template. Format the file corresponding to these files, copy it to this folder and then restart camSPECS.

Wavelength (nm)	Intensity
380	24.49
385	27.18
390	29.87
...	...
770	82.92
775	80.6
780	78.27

3. Select the ColorChecker reflectance data. This data contains the spectral distribution between 380 and 730 nm in 5 nm increments.
4. Select an RGB image file from a ColorChecker test chart (ColorChecker with 24 patches or Color Checker SG with 140 patches). The image must be a raw image file. Do not use compressed image formats like JPEG or other output-referred encodings since source colors have been rendered.
5. Select a dark image for subtracting from the ColorChecker image (optional). The size of this image and the ColorChecker image must be the same.
6. After clicking the *Start* button, the selected ColorChecker image is opened and displayed. Select the chart by drawing a rectangle around the patches from upper left to lower right and double-click on the rectangle. The ROIs for each patch are displayed in the next step and can be rearranged manually. Double-click outside ROIs to continue.



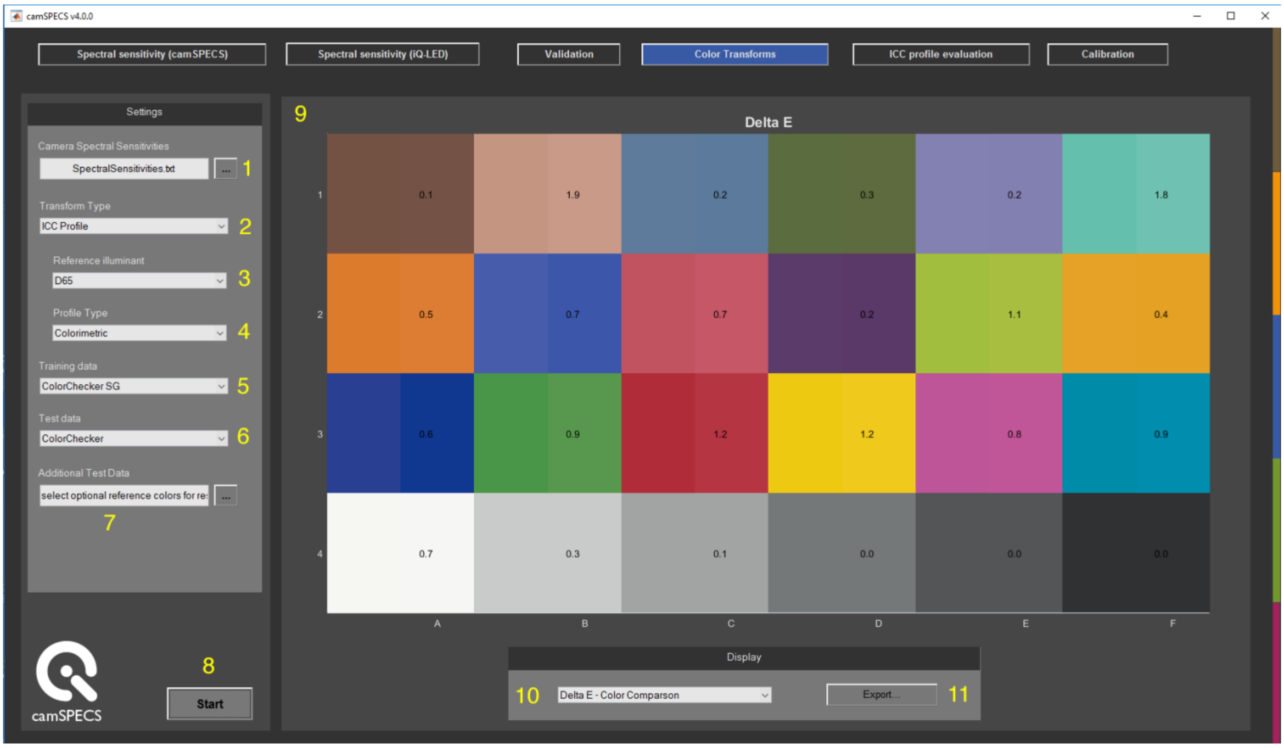


7. Export the validation graph to an image (JPEG, PNG, TIFF, BMP, GIF) for documentation purposes.

The validation verifies the processing chain from the exposure of the ColorChecker images (surrounding light conditions, camera lenses, raw image converting, etc.) to the spectral response measurement with camSPECS. In the displayed result, each patch's measured digital values (red, green, and blue) are plotted against the predicted digital values. All values are normalized to a range between 0 and 1. If the exposure and measurement setup is highly accurate, all RGB data points in this plot should be close to the white diagonal line (best correlation). Possible reasons for significant variations may be changes in the illumination of the ColorChecker or manipulations of the RGB data within the camera.

4.8 Color transforms module

The color transforms module computes various color transforms from the measured camera spectral sensitivities for several different types of transforms.



1. Select a Camera Spectral Sensitivities file (.txt) with values interpolated to 5 nm (see advanced settings) created by camSPECS.
2. Select the desired transform type from those available.
   - *Matrix – Colorimetric* creates a 3x3 matrix from camera RGB to XYZ for the specified Reference illuminant.
   - *Matrix – White point preserving* creates a 3x3 matrix from camera RGB to XYZ constrained for white balance to the specified Reference illuminant.
   - *ICC Profile* creates a transform from camera values (assuming white-balanced image data) to the International Color Consortium Profile Connection Space (PCS) and is chromatically adapted from the specified Reference illuminant to ICC PCS illuminant D50. Several Profile Types (4) are available:
     - *Colorimetric - Matrix* creates a standard matrix-TRC profile using a 3x3 matrix from camera RGB to XYZ and gamma=1 in the TRC (tone reproduction curve).
     - *Colorimetric - CLUT* creates an exposure-invariant 3D color lookup table (multidimensional lookup table - MLUT) and gamma=1 in the TRC, giving improved accuracy and flexibility.
     - *Rendered - CLUT* creates an exposure-invariant 3D color lookup table (multidimensional lookup table - MLUT) and user-specified gamma in the TRC. This option is helpful in applications such as PhaseOne CaptureOne, which expects gamma = 1.8 for the default rendering and linear mode.
     - *ACES* (Academy Color Encoding System), used in the motion picture industry, create a CTL (Color Transformation Language) file that encodes a colorimetric transform that can be used with

CTL interpreters and a JSON (JavaScript Object Notation) file that encodes the spectral sensitivities for use with Raw-to-ACES applications. These are text files that are user-editable to facilitate the specification of other workflow-specific parameters, but options are provided for:

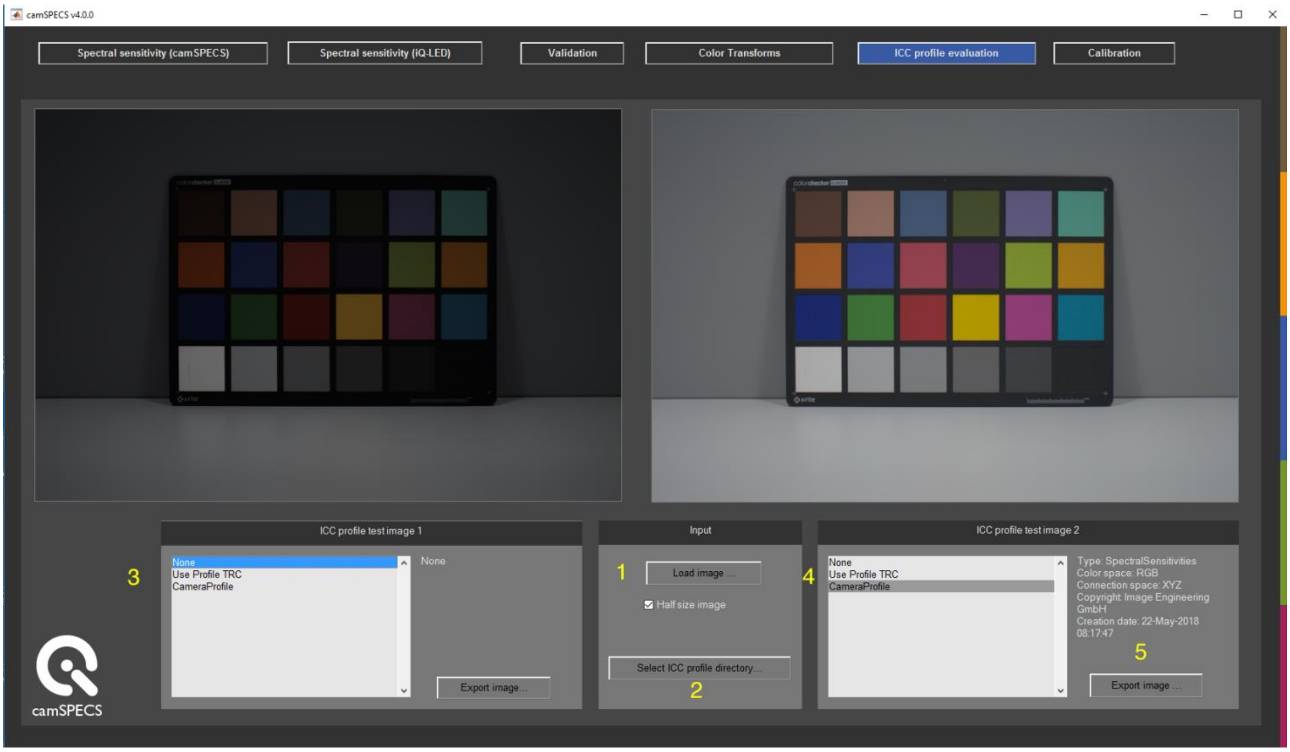
- *Exposure headroom* specifies in luminance-linear units the amount of encoding range above camera-assumed diffuse white to allow for specular highlights.
- *White Balance* is the factor required to balance the camera channels to diffuse white. The default values are computed from the integral of the spectral sensitivities.

Luminance creates a transform optimized to the CIE luminosity function (Y) without regard to colorimetric performance and assuming equal energy illumination (E).

3. Select the desired Reference illuminant spectral distribution file for the scene's light source adopted white point. For respective light sources, see chapter 0, item 1.
4. Select the desired Profile Type as described above.
5. Select reflectance Training data. The resulting camera transforms will be optimized for the selected combination of Camera Spectral Sensitivities and the Reference illuminant, which minimizes errors in predicting the Training data. The data are spectra between 380 and 730 nm in 5 nm increments. Other data apart from ColorChecker data can be used, for example, iQ in-situ data (see chapter 4.11). New files can be added to the corresponding directory in the camSPECS software (/calibration_files/reflectance). Make sure to restart camSPECS to use the new files in this menu. An optimal camera can be built by obtaining the in-situ data and installing it in the C:/Program Files/Image Engineering/ camSPECS folder.
6. Select the desired reflectance Test data that will be used to evaluate the camera transform. The test data is evaluated through the transform, and the results are written to the log file ctbErrorsCIECAM16 once the camera transform has been computed.
7. Optionally, Additional Test Data can be selected to input additional test spectra to be used to evaluate the camera transform.
8. Click *Start* to generate the specified transform.
9. The results panel shows the performance of the transform. By default, a visual representation of the Test data is shown in a split field for each color patch. The left field for each patch shows the original color, and the right field shows the color resulting from the transform applied to the original color spectra, assuming the display is calibrated to the sRGB standard. The numerical values show the CIECAM16 color differences between the two fields.
10. The display shows the results from the computed transform in several forms:
    - *Delta E – Color Comparison* is the default described in step 9 above.
    - *Delta E – Heat Map* shows the results categorized and color-coded per the maximum user-specified tolerance in Delta E range.
    - *Spectral response comparison* shows the CIE 1931 standard colorimetric observer color matching functions, the camera spectral sensitivities, and the prediction of the color matching functions resulting from applying the transform to the camera spectral sensitivities.

11. Click *Export* to save the transform.

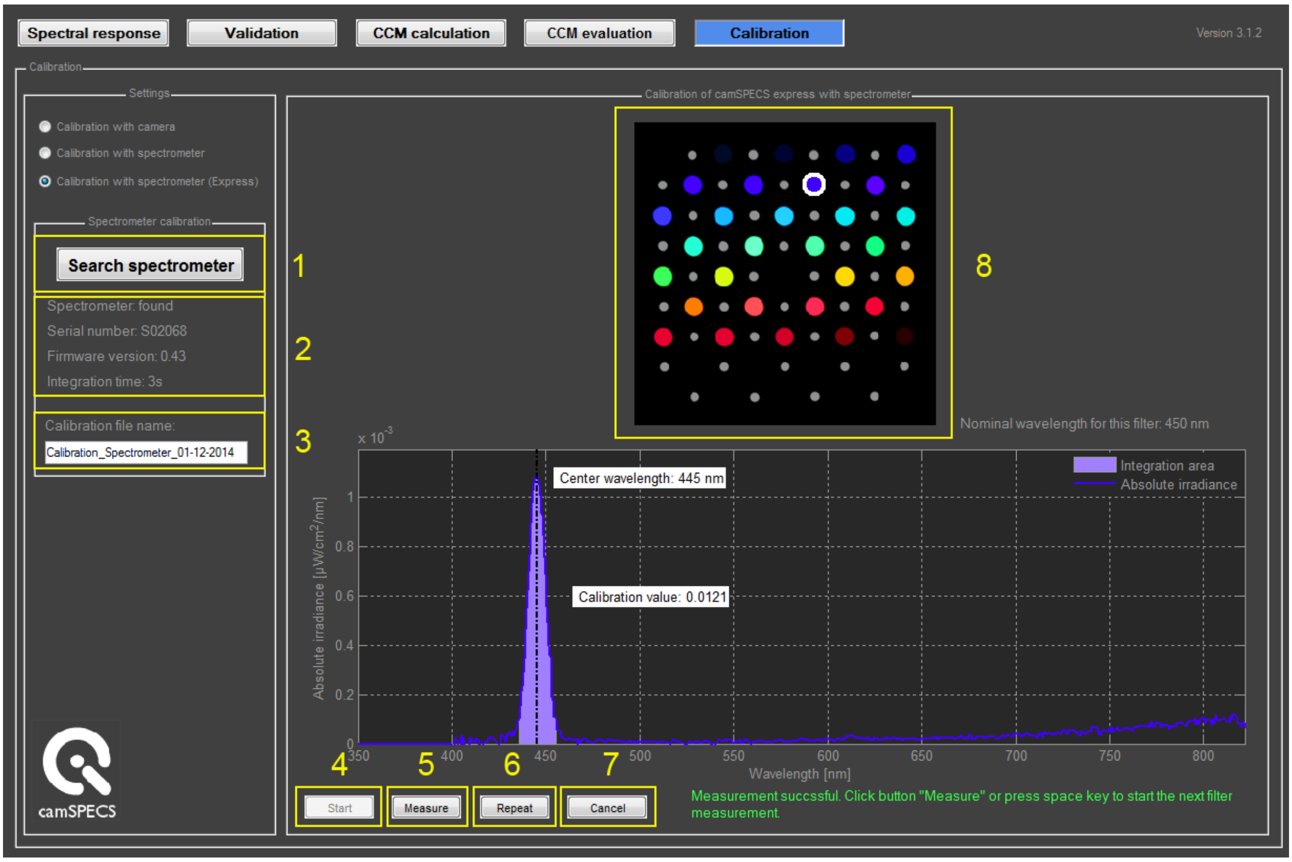
4.9 ICC profile evaluation



The ICC profile evaluation module shows two windows with the same image. In either window, an ICC profile may be selected, applied to the image, and the image converted to sRGB for display on an sRGB-calibrated monitor.

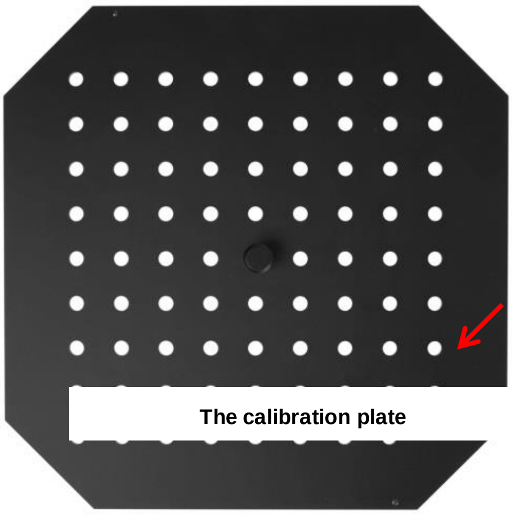
1. *Load Image* selects a raw test image captured under the same illumination for which the ICC profile was computed. The image will be opened and converted from raw to white-balanced, 16-bit, linear RGB. If checked, the half-size image option reduces the image size for faster processing and viewing.
2. *The ICC profile directory* selects the directory where ICC camera profiles are located or saved in the Color Transforms module. Always select the directory for each use to refresh the contents and enable Use Profile TRC. *Select Display Profile* allows the selection of the ICC profile of a calibrated monitor for which a color-managed match is desired. If this profile is not specified, matches to sRGB are produced in this module based on the assumption that an uncalibrated monitor will be similar to the sRGB standard.
3. *ICC profile test image 1* selects from a list of ICC profiles. To view the raw image, select *None*.
4. *ICC profile test image 2* selects from a list of ICC profiles. Select the ICC profile created in the Color Transforms module to view the image color managed for viewing on an sRGB device. The color-managed image has the camera color transform, and the display tone reproduction curve is applied. Toggling amongst the profile, None, or Use Profile TRC allows separate visualization of the effect of both components.
5. *Export image* saves the white-balanced, 16-bit, linear RGB image with the ICC profile embedded.

4.10 Calibration



A calibration device is delivered with the camSPECS hardware. A positioning plate for the aperture of the fiber is also included in the delivery. Easily place the plate in front of the filters and mount it, so the missing hole is at the bottom right (see the image below). There is no filter at this position on the front side of camSPECS. Insert the measurement head securely in each hole of the plate.

Now plug the calibration device with the USB cable into the computer and switch to the *Calibration* module. If the calibration device is detected, the radio button *Filter Calibration* is selectable, and some information about the connected device is displayed. The calibration procedure should be carried out in a dark place and requires approximately 10 minutes. The order of the filters measured includes a dark measurement first, followed by all color filters from upper left to lower right, and finally, all the neutral density filters from upper left to lower right. Before switching to the ND filters, perform a second dark measurement. Each measurement's result is displayed: the spectral distribution, the center wavelength of the filter peak, and the calibration value. The calibration value is the area under the curve (AUC) in the interval with the lower and upper limits specified at the 10 % threshold of the



The calibration plate

peak value. A failed measurement may be repeated, e.g., if a wrong filter was measured. The next filter in the queue is highlighted in the display of the camSPECS filter matrix. After the measurement procedure is finished, a new calibration file is created and is immediately available in the spectral response module.

Note:

The calibration device has a temporal temperature dependency, which may influence the intensity measurement of the filters. It is, therefore, necessary to plug the device into the PC with the USB cable at least 10 minutes before the start of measurement. This time is needed to heat the calibration device to a working temperature.

Description of the numbered controls marked in the overview image of this chapter:

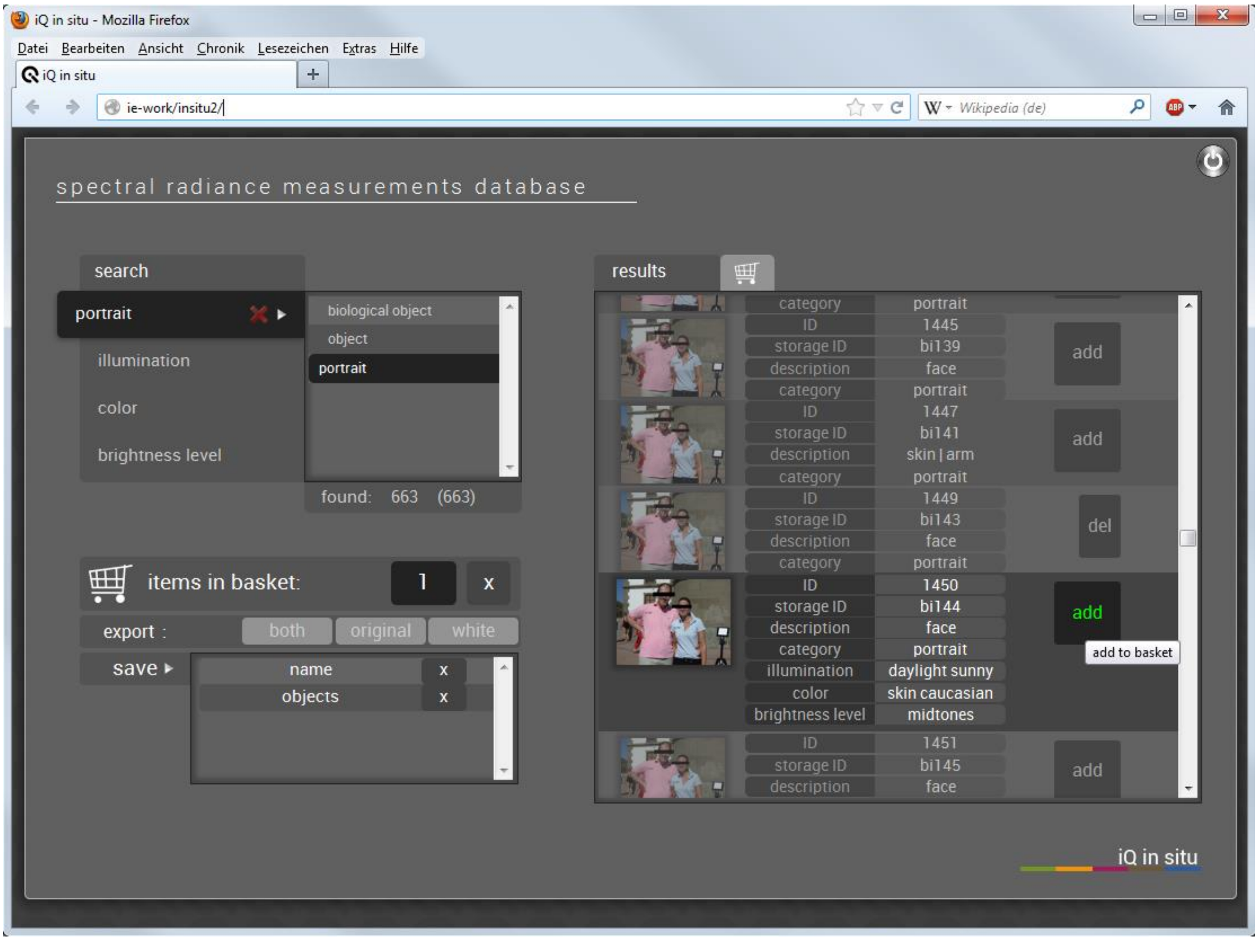
1. Click the button *Scan for calibration device* to scan USB devices for a connected device. In some cases, it is necessary to disconnect and connect the calibration device from the computer and then search again.
2. If a connected calibration device is available for measurement, some information is displayed here: the serial number, the firmware version, and the integration time for one filter measurement.
3. In this editing field, a name for the final calibration file can be edited; it has the form "Filter_calibration_DD-MM-YYYY by default. This name displays the spectral response module in the menu *Calibration file* (chapter 4.5).
4. Put the covering cap onto the aperture of the calibration device or shade it completely by other means. The calibration procedure is initialized with a dark measurement by clicking the start button, and the *Optimize integration time* button will be active for a supported spectrometer. If selected, directions are stated above detailing the proper sequence of dark readings and color filter readings specified in the spectrometer_settings.txt file. If this function is selected, the default values in the spectrometer_settings.txt will be updated with the optimized values. It is essential not to move the spectrometer probe until the text under the spectral plot window shows that the iterative optimization is finished, and the measurements are complete. Next, all filters must be measured. Remove the cap from the aperture of the calibration device and measure the filters highlighted in the image above [8].
5. Place the measurement head in the upper left hole, which is the first filter to be measured. Click the *Measure* button. Check the result in the graph: The calculated center wavelength may differ from the nominal value but generally not more than ± 2 nm. The nominal value for the current filter is also displayed right beneath the overview image [8].
   If the result is unsatisfactory, repeat the measurement by clicking the button *Repeat*. Only the last measurement can be repeated. After all color filters are measured, the subsequent measurement is the ND filters. Please remember that another dark measurement is required between each filter.

Continue measuring the ND filters. Finally, the calibration file is generated and saved to the disk and is directly available in the spectral response module.

6. This button repeats the last measurement. Always check the resulting spectral distribution of the filter and the center wavelength after each measurement for reliable results and repeat the last measurement if it seems insufficient. This issue may happen, for example, when the measurement head is not inserted entirely, and the measurement is started too early.
7. Clicking the *Cancel* button stops the whole calibration procedure and discards all previous measurements, and the calibration procedure needs to be started again.
8. The following filter to be measured is displayed in the image.

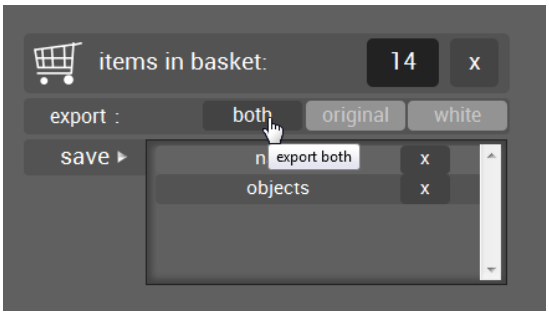
Mount the calibration plate in front of the filters and tighten it with the screw cap.
Push the measuring head into the holes of the calibration plate as far as it will go.

4.11 Use of the in-situ database



For calculating color transforms and profiles, spectral reflectance values are needed as training data. By default, the patches of a ColorChecker or ColorChecker SG are used as objects for this purpose. The corresponding files can be selected in the menu of the CCM calculation module.

For improved results, training data is available in the iQ in-situ database (http://insitu.image-engineering.de). In this database, the spectral radiances of more than 2000 natural objects under various illuminations are available. Choose a couple of objects in the database and add them to the basket (see figure above). For example, to choose skin colors, select images from the category "portrait." Increasing the number and diversity of selected objects will improve the calculation of the color transform for those objects chosen. Now export the spectral radiance values by clicking the "export / both" button. The data is saved as a .csv file that then needs to be copied to the directory C:/Program Files/Image Engineering/ camSPECS V…/calibration_files/reflectance" to make it available for CCM calculation. After a restart of camSPECS, the new radiance data is available in menu "Training data" in the



CCM calculation module. After calculation and export to an XML file, the resulting matrices may be evaluated in the CCM evaluation module.

4.12 Known issues

A long file or network path can cause problems when using 'dcraw.' Use short paths on the hard disk for the images.

4.13 Trademark and Copyright

Trademarks

Windows is a registered trademark of Microsoft Corp. and Matlab is a registered trademark of Mathworks Corp.

Software by Third Parties

dcraw -- Dave Coffin's raw photo decoder
Copyright 2016 by Dave Coffin
dcoffin@cybercom.net (www.cybercom.net/~dcoffin/dcraw/)

Copyright Information

See separate Terms and Conditions document.

5 ADDITIONAL INFORMATION

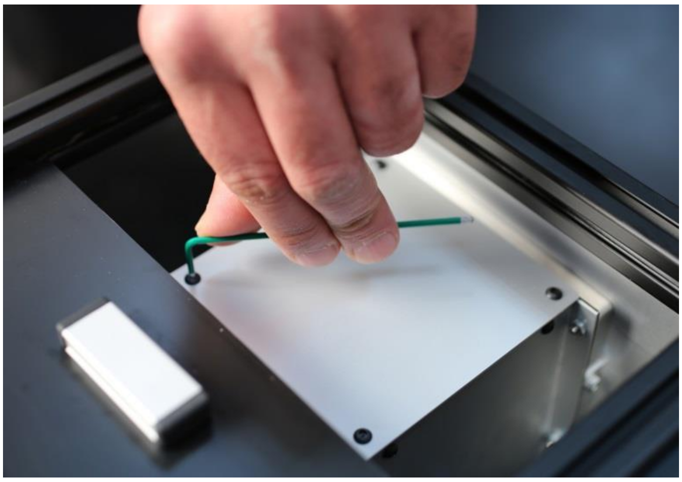
5.1 Maintenance

camSPECS does not need any special maintenance.

- **Do not** touch or pollute the surfaces of the filters.
- Remove dust on the filters with pressurized-air spray.
- Remove undesired fingerprints or fat on the filters carefully with a soft and dry tissue.

If the bulb is defective, replace it with the replacement bulb:

- Open the sliding port on the top side of camSPECS.
- Remove the top cover of the lamp housing by releasing the four screws with an Allen key.



- Remove the old bulb.
- Insert the new bulb. **Do not touch** the new bulb with bare hands or fingertips, use a tissue or fabric gloves.

The calibration device requires a recalibration yearly, regardless of the operating hours. If calibration is necessary, please contact Image Engineering.

- Do not touch, scratch, or pollute the measuring head.
- Do not remove the fiber from the calibration device; otherwise, the calibration is invalid.

5.2 Disposal instructions

After the service life of camSPECS and the spectroradiometer, they must be disposed of properly. Electrical and electromechanical components are included in camSPECS and the spectroradiometer. Observe all national regulations and ensure that camSPECS cannot be used by third parties after disposing of it.

Contact Image Engineering if assistance for disposal is required.

6 TECHNICAL DATASHEET

See annex for the technical data sheet. It can also be downloaded from the website of Image Engineering: https://image-engineering.de/support/downloads.