Application Note

AN000633

Spectral Sensor Calibration Methods

AS7341 EVK Evaluation Kit

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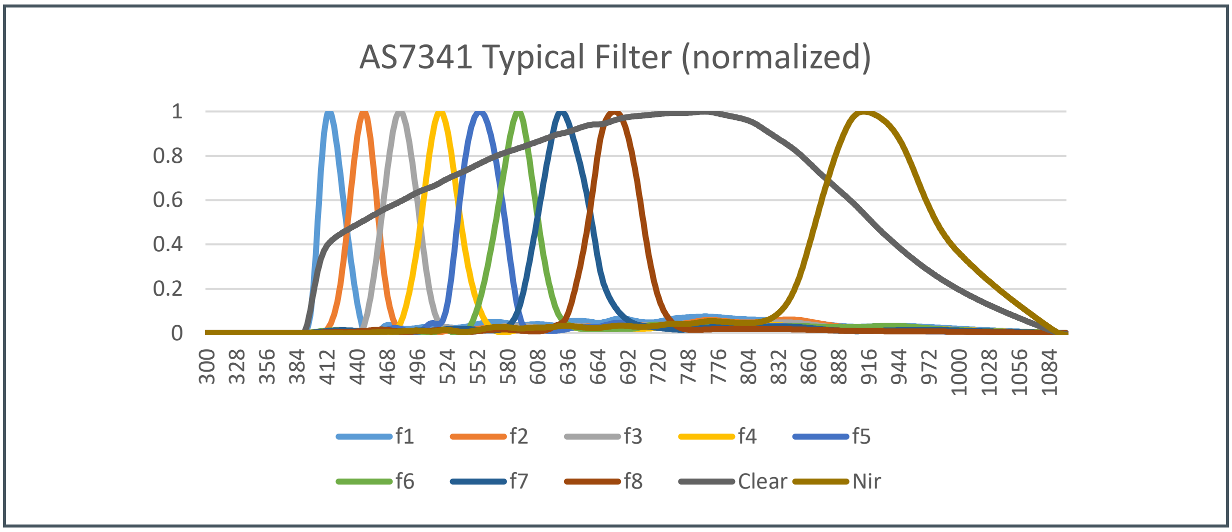
1 General Description

This Application Note describes how to implement correction and calibration methods by considering different effects based on the Spectral Sensor (and derivatives) Evaluation Kits (EVKs). It shows various steps, procedures, and approaches used for alternative methods of spectral and multi-spectral sensors. Everything is explained using the AS7341 example. Other spectral sensors are similar in spectral technique, differing in the number of filters and peaks, but not in the algorithm and spectral sensor correction functions shown here. Therefore, the details shown here for the AS7341 example can also be used for all other similar spectral sensors with adaptation.

1.1 Filter Correction

The AS7341 is an 11-channel Sensor for spectral identification and color matching applications. The spectral response has a wavelength from approximately 350 nm to 1000 nm. Eight optical channels cover the visible spectrum. One channel can be used to measure near-infrared light. The ‘Clear’ channel is a photodiode without a filter (‘clear’) for monitoring tasks, and the ‘Flicker’ channel is prepared for flicker measurements.

Figure 1 :
Typical Spectral Behavior of Each Channels in AS7341 (Sensitivity ‘1’-normalized)



The spectral filters, in combination with the diodes and electronics, provide details about the measured spectrum of the light on the sensor. The sensor results are dependent on the sensor arrangement and other direct effects such as series-related disturbances and deviations, as well as effects in the measuring process itself. Therefore, in a final system setup, a correction of the raw sensor values is necessary to eliminate the unavoidable disturbance effects and deviations. Furthermore, the conversion of the sensor results as raw digital values into physical parameters (the application) is necessary after the correction of the influences and can be part of the correction and calibration.

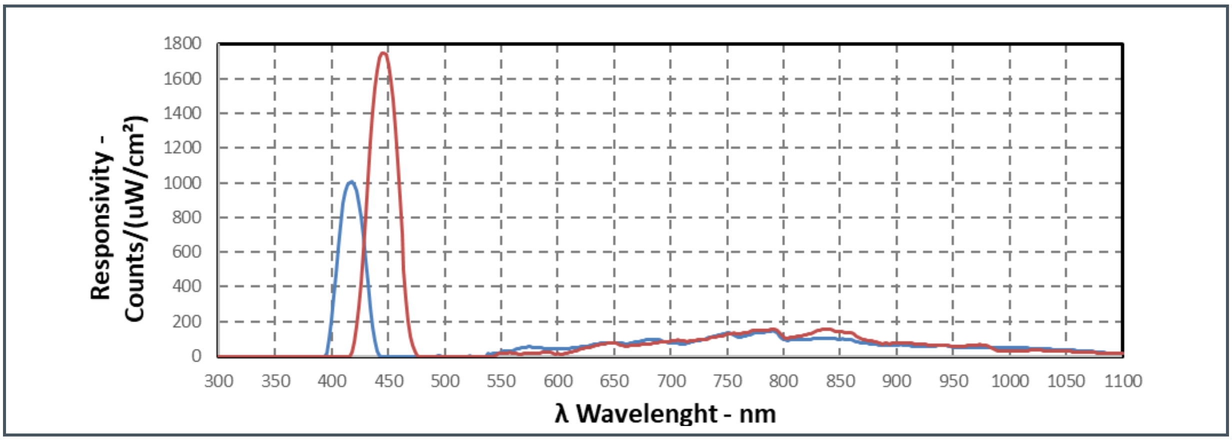
Theoretically, a narrow band filter in spectral Sensors should only allow a unique light frequency that matches the filter spectrum in transmission to pass through (like a spectrometer).

In practice and for the AS7341 sensor specifically, the transmission range and blocking outside of it is not ideal, resulting in optical interference. Secondly, the filters and sensitivity are not in ideal form. They are sometimes different in wavelength and vary slightly in the series in the specimens and lots.

Figure 2 shows the sensor-specific spectral response of filter 1 and 2, filter overlapping (doubled active filter in transmission), and also the spectral values of the channels are not limited to the exact band wavelength (transmission and filter function), instead it has an out of band spectral value in VIS and NIR (rest transmission in blocked wavelength). This is due to the opening of the optical channel band filters and affects the Sensor results.

For other sensors, it looks similar but different. Scaling factors, matrices, or special algorithms during the calibration and correction process will reduce such effects.

Figure 2:
AS7341 Channel F1 + F2 Spectral Response with Filter Overlapping and Rest Transmission



1.2 Diffuser Compensation

The photodiodes inside the AS7341 or other spectral sensors have a near cosine response to incoming light. Typical spectral filters used for channel separation are specifically developed interference filter stacks on top of the photodiodes. Due to physical influences in the filter stacks, the interference filter technology is limited for an incidence angle range (AOI) and expects a Lambertian power distribution. The maximum angle of incidence to the photodiodes is limited to the design requirements of the filter stack by the aperture/pinhole of the package. The rays with the most obtuse angle hit the edges of the photodiodes form the opposite edge of the aperture. It is necessary to get a diffused light on the Sensor to meet these requirements of power distribution. In the case of a non-diffuse application, the use of an achromatic diffuser is required, which emits light with Lambertian characteristics to the Sensor, regardless of the angle of incidence. If the diffuser is very close to or directly on the sensor package, then its structure has to be very fine to get the same distribution to each photodiode of the detector array. On the other side, the diffuser also changes the spectral response and transmission of the Sensor system because they always have their specific transmission curve, which is greater than zero and not constant. Therefore, a correction of the diffuser transmission may be required as one part within the calibration. The manuals list more details for diffusers and EVKs.

1.3 Disturbances

Disturbances influence the Sensor results statically or dynamically. To obtain optimum results, a verification and optimization process must correct or eliminate all these negative effects. The following list includes some examples, which can affect the accuracy, more or less depending on the application.

- Basic noise (e.g. dark current)
- Non-linearity Integration Time
- Gain Error
- Temperature and ageing effects from Sensor and luminary (e.g. LEDs)
- Ambient Light
- Reflections inside the Sensor System

Examples of such faults and their possible corrections can be found on the following pages.

1.4 Measurement Setup and Parameters for Measurement Accuracy

For Sensor applications, the measurement setup and optical stability play a crucial role in accuracy and calibration. For the purpose of calibration, the most stable and reliable measurement setup is selected. Monochromatic test systems and/or spectrometers are required as reference devices to specify the target pattern, check the behavior of the light source, and proof the test setup. Further, they are important to verify the Sensor results and their corrections/calibrations. Reference devices are depending on the sensor’s dynamic range and should be active for AS7341 from VIS (UV) to NIR, with a spectral range of 350 nm to 1000 nm. The highest accuracy for a reference device is essential when high accuracy for the Sensor is expected. The reference instrument should be at least ten times more accurate or higher than the sensor requires.

The test setup should be stable and free of any disturbances and drifts. They must be checked individually and systematically for each application, possibly after adding modules, to obtain applications typical or device-specific correction values.

Use the Sensor EVK for feasibility projects. The hardware, software, and adapters have been designed to be stable and ensure high accuracy for standard applications. However, the EVKs consists of bare hardware and are not shielded against any environmental conditions. They also only supply digits and raw values. Therefore, the customer has to adjust the EVKs + results and the calibration + corrections for their specific application. For more details, please refer to the Sensor ECGs manual.

2 General Correction

2.1 Calculations with Basic_Counts

Sensor results depend on Sensor specific setup - the selected parameters for Gain (AGAIN) and Integration Time (TINT). However, changing these parameters under constant conditions in measurement should not change the real Sensor response – RawSensorValues. On the other side, ADC results are directly dependent on and more or less proportional to Gain and TINT[1]. The higher the Gain and TINT, the better the ratio between signal and noise. Raw_Counts (= Raw Sensor Values) from the ADC must be transformed into a result, which is not dependent on the parameter setup but should achieve a maximum as possible. All Sensor calculations are on Basic_Counts. The definition is:

Equation 1:

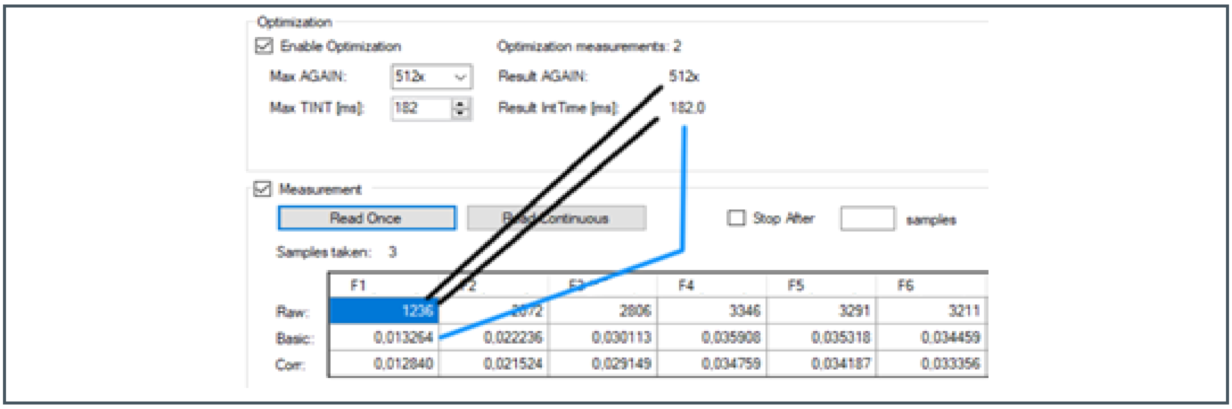
$$\text{Basic\_Counts} = \frac{\text{Raw\_Counts}}{(\text{Gain} \times \text{Integration Time})}$$

Figure 3 shows an example from a protocol file with Setup, Raw_Counts, and Basic_Counts.

The Basic_Counts in this example for F1 is calculated by:

$$0.013264 = 1236 / (512 * 182)$$

Figure 3 :
Example for Basic_Counts



[1] TINT (Integration time) selection can affect the counter for the sensor results. It means TINT directly determines the Full Scale Range and saturation.

For all corrections and calibrations, always use Basic_Counts or other calculated values without dependence on the setup and parameters, especially for dynamic gain and the like.

2.2 Offset

Offset is defined here as a constant interference signal that continuously affects a Sensor via the measuring process, for example, dark values, ambient lighting, or overcrossing. Each sensor channel has its offset characteristics. Therefore, consider offsets individually per channel.

The first step of the correction is to measure the offset. This often requires a special device setup. It is also recommended to check more than one Sensor to see their individual, lot, and series deviations. Averaging can be a method to get an approximated and typical value for correction or to use the individual offsets as part of a single device calibration.

The second step is to calculate or define correction values based on the offset measurements (and averaging). These offset correction values will reduce the raw Sensor values in the sensing process by a simple subtraction:

Equation 2:

$$\text{SensorCorrectedValueOffset} = \text{Basic\_Counts} - \text{Basic\_CountOffset}$$

The offset can be set in the GUI initialization and calibration files, as shown in the following example. It is important to use for offset correction always the Basic_Counts.

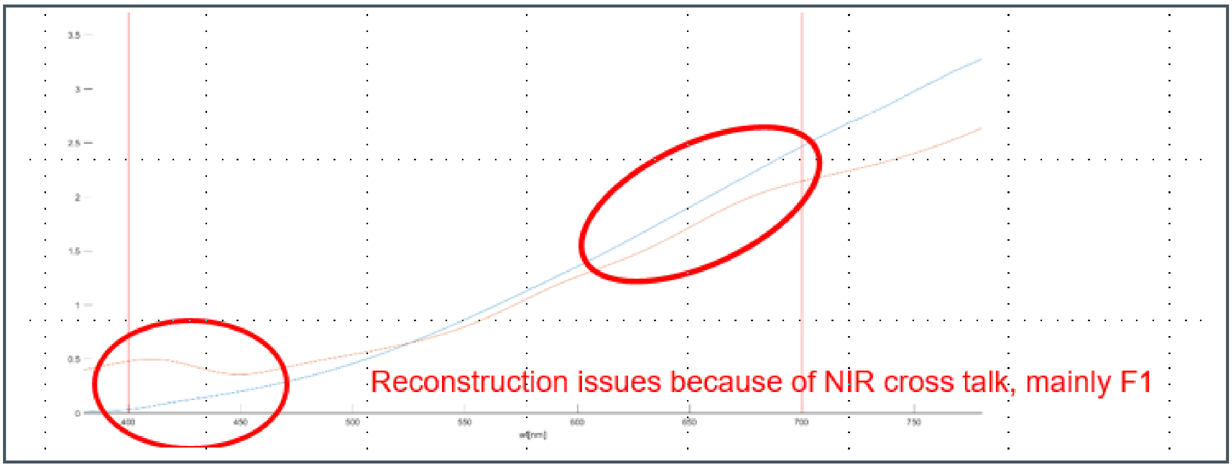
Figure 4 :
Example Calibration Files with Specified Offset and Factors for Corrections in EVK

```
//OffSet values decreases Basic values - example Pen
OffSet=0.009906;0.027358;0.013936;0.04078;0.046826;0.05566;0.042624;0.03289

// Correction factor of Raw values
CorrectionFactor=0.55500034;0.454630147;0.485751323;0.511139519;0.482990316;0.531305638;0.534095036

//Correction factor for gain error
//0.5x.1x.2x.4x.8x.16x.32x.64x.128x.256x.512x
CorrectionGain=1.0240;1.0240;1.0240;1.0400;1.0000;1.0000;1.0000;1.0000;1.0000;0.9875;0.968

//correction factor to correct Y as Lux from CIE1931 Y
corr_lx = 683

//Correction in VIS based on NIR filter to correct overcrossing from NIR
NIR_Corection = on
```

2.3 NIR Correction

Figure 2 shows the transmission and rest transmission for two AS7341 filters (F1 + F2). Spectral reconstruction creates some issues for light spectra with huge NIR parts (e.g. filament lamp). In these cases, the matrix algorithm will badly interpret the NIR crosstalk of the channels F1 … F8, and the colorimetric calculations will get colder than warm-white. Therefore, the rest transmission affects the sensor results, depending on the NIR size and series tolerances. NIR effects are typical but also individual. In general, the higher the rest transmission, the greater the error if it cannot be corrected. Offset or matrixing methods can correct rest transmission in case of it is constant over time, and the sensor system was prepared to correct it. However, NIR radiation can affect an application and does not necessarily have to be constant over time and within applications. Therefore, if NIR is an unknown effect or is unstable for measurements, then special situational methods are necessary.

Figure 5:
Reconstruction Issues Based on NIR Crosstalk (Red = Reconstructed ; Blue = Mask)



The following pages show a method of using typical measured filter values to show typical corrected results. Nevertheless, if such results can be replaced by an individual calibration (device calibration), then the accuracy for such results of this NIR correction can increase. The method presented here is based on the known proportions of the rest transmission of the F1...F8 filters in NIR[2] and relates these to the measured values of CLEAR and NIR per measurement, to determine the NIR proportion for correction in the individual channels F1...F8.

From the sensitivity spectra ($S\lambda$ for all filters of AS7341 F1…F8, see Figure 1), the ratios between the single Fn sensitivity values and ‘Clear’ filter values at peak n (for F1 at 410nm etc.) can be calculated from the design data[3]. For general calibration, typical data from a table (Figure 6) are used here as values. For individual calibration, calculations from reconstructed sensitivity spectra will increase accuracy.

[2] From the design’s data filter specifications, and typical measurements - with acceptance of typical values of the spectra NIR crosstalk of each sensor channel F1 … F8, it is possible to estimate the NIR part in the sensor signals, and from this an estimated compensation (weighting of the signals) is possible.
[3] peak = wavelength with maximum of sensitivity

Equation 3:

$$S\lambda\_scaling_{k\ (1:8)} = \frac{S\lambda_{k,\lambda_{k,peak}}}{S\lambda_{Clear,\lambda_{k,peak}}}$$

Equation 4:

$$S\lambda\_ratio\_NIR_{k\ (1:8)} = \frac{\int_{1100}^{750} S\lambda_k(\lambda)}{\int_{1100}^{750} S\lambda_{Clear}(\lambda)}$$

Figure 6:
General Values for Sλ_scaling and Sλ_ratio_NIR

	F1	F2	F3	F4	F5	F6	F7	F8
Sλ_scaling	1.48	1.87	1.85	1.92	1.79	2.0	1.92	2.32
Sλ_ratio_NIR	4.47%	5.51%	5.31%	6.15%	3.91%	7.01%	5.31%	4.28%

In the NIR correction process for an actual measurement, the first step is to balance the filter results F1…F8 (D_Basic – Basic-count Sensor) by using typical or individual Sλ_scaling factors (Equation 3). Results are D_scaled_to_Clear as 'Clear' scaled/balanced Sensor results F1 ... F8.

Equation 5:

$$D\_scaled\_to\_Clear_{n,k} = \frac{D\_Basic\ n, k}{S\lambda\_scaling_k}$$

D_scaled_to_Clear are then the new scaled to clear sensor results for all channels for following calculations.

Equation 6:

$$D\_Clear\_NIR_n = \frac{D\_scale\_to\_Clearn_{Clear} - \sum_{k=1}^{8} D\_scale\_to\_Clearn_k}{D\_scale\_to\_Clearn_{Clear}}$$

D_Clear_NIR (Equation 6) is the ratio between the balanced integral of 'Clear' and the filter channels F1 … F8. It represents the signal ratio in 'Clear' and NIR.

Equation 7:

$$D\_F\_NIR_{n,k} = S\lambda\_ratio\_NIR_k * D\_Clear\_NIR_n$$

The D_F_NIR (Equation 6) represents the sum of sensitivities of 'Clear' outside the wavelength of the visible range. In this estimation, the sum of all scaled channels F1:F8 is set approximately equal to the sum of the sensitivities of 'Clear'. All inaccuracies in the estimation are therefore accepted.

NIR_weight (Equation 8) is the calculated ratio of NIR and 'Clear' results of the actual measurement. The used factor of 0.1 represents a correction factor to compensate for different diode sizes of the NIR and 'Clear' channels.

Equation 8:

$$NIR\_weight_n = 0.1 * \frac{D\_Basic_{\,n,NIR}}{D\_Basic_{\,n,Clear}}$$

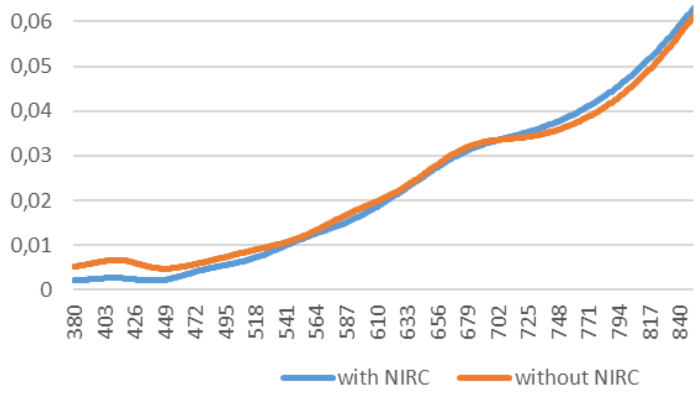
Equation 9 corrects the measured value of the filters by the scaled portion of 'Clear' in NIR. Here, the already calculated or typical ratios of actually Clear to NIR, typically F1 to F8 to NIR as well as the ratio of 'Clear' in NIS and VIS are calculated together as a correction of channels F1 to F8.

Equation 9:

$$D\_w_{n,k} = D\_Basic_{n,k} - D\_F\_NIR_{n,k} * NIR_{weight_n} * S\lambda\_ratio\_NIR_k$$

The results for filters 'Clear' ($D\_w_{n,Clear} = D\_scal_{n,clear}$) and NIR ($D\_w_{n,NIR} = D\_scal_{n,NIR}$) do not change. It means they will not be corrected by the algorithm.

Figure 7:
Reconstructed Spectrum of Standard A Light Source with/without NIR Correction (1)



(x-wavelength, y-relative sensitivity in Basic_Counts)

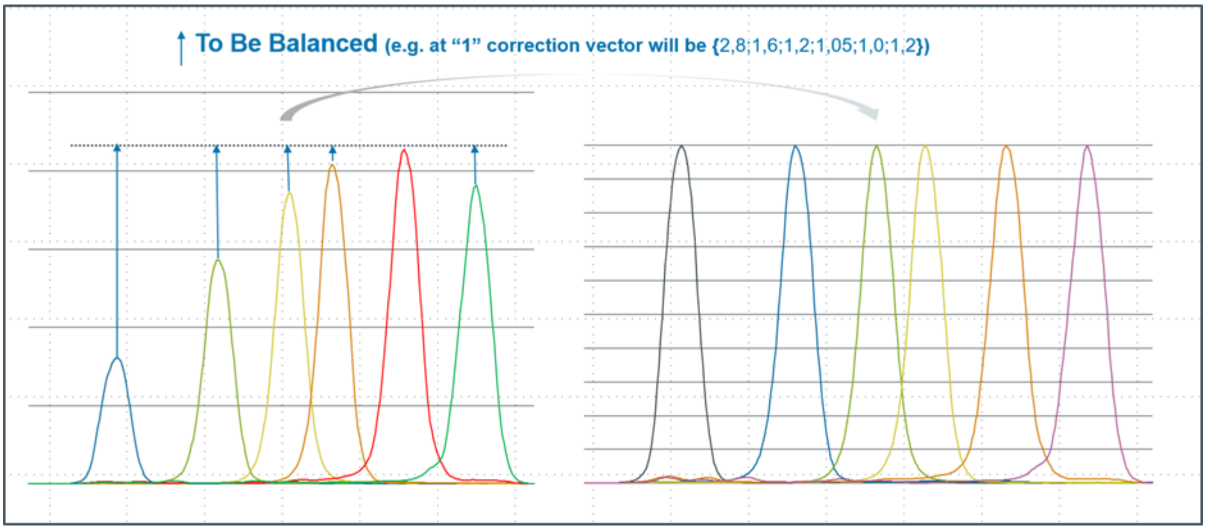
(1) **ams** offers a published XLS sheet where all formulas of the NIR correction can be followed with an example like shown in this diagram.

The result of the NIR correction with this algorithm is a modified corrected spectrum, with reduced signals in channels 1-8 corresponding to the NIR portion of the current measurement. Here, the correction of all sensors is carried out with standard values from a typical sensor. The result is always good, depending on the current sensor from the typical sensor. Therefore, the NIR correction may also worsen the result if the deviation from the typical sensor is large, and the NIR portion of the measurement is very large. Figure 8 shows an example as a diagram, before and after the NIR correction.

2.4 Normalization / Scale

Scale procedures are corrections when Sensor results show a percentage error compared to reference values. Such values can be the results of targets measured by reference. In general, the correction factor for each channel is the result of a balancing of reference values and Sensor readings. The result of scaling is a correction vector, which includes correction factors for each Sensor channel. All values are Basic_Counts.

Figure 8 :
Spectral Channels Before and After '1'-Scale (or Balance)



Scaling procedures are often used to adjust the behavior of Sensors for one defined reference point, e.g. the minimum, maximum, or any other point from the series test (Figure 8).

According to the objectives, a one-point correction or two-point correction is applied. A typical formula for such a scaling using one reference point is:

Equation 10:

$$\text{SensorCorrectedValueScaled} = \frac{\text{ReferenceValue}}{\text{SensorCorrectedValueOffset}}$$

One-point correction means the Sensor response of all Sensors in an application will be calculated to be scaled at One-point (e.g. Minimum min, Maximum max, or somewhere between min and max). The title of this method is 'White or Black Scale'.

In case the Sensor results are normalized between Two-points (e.g. 'Dynamic Scale' or 'Black/White Scale'), then these Two-points will be used in the formula:

Equation 11:

$$\text{SensorCorrectedValueScaled} = \frac{(\text{X} - \text{Xmin})}{(\text{Xmax} - \text{Xmin})}$$

Here, X is $\text{SensorCorrectedValueOffset}$ and Xmin/Xmax are the two Reference Values min/max.

Figure 9 and the following figures show an example for scaling in a light application.

The example describes the light detection via the spectral Sensor and inserts the spectrometer target data (Figure 9), the Sensor results as raw Sensor values, and the corrected Sensor results after scaling (Figure 11).

The correction uses scaled ‘Sensor values to spectrometer targets’ for one defined light source – daylight used here. The result of scaling is the correction vector, which includes for each channel a value representing the deviation Sensor RAW to spectrometer (Figure 10). These correction values are useful to correct Sensor results also for other light sources. In the example, a Daylight source and its results and target show the accuracy of the Scale procedure.

The results in the diagram(s) are good for such a primitive correction method but can be better using matrices. The difference between scale and matric methods is the number of used targets. A higher number of reference targets can increase accuracy for calibration dramatically.

Figure 9 :
Comparison Spectrometer Results and Sensor RAW Data for Daylight

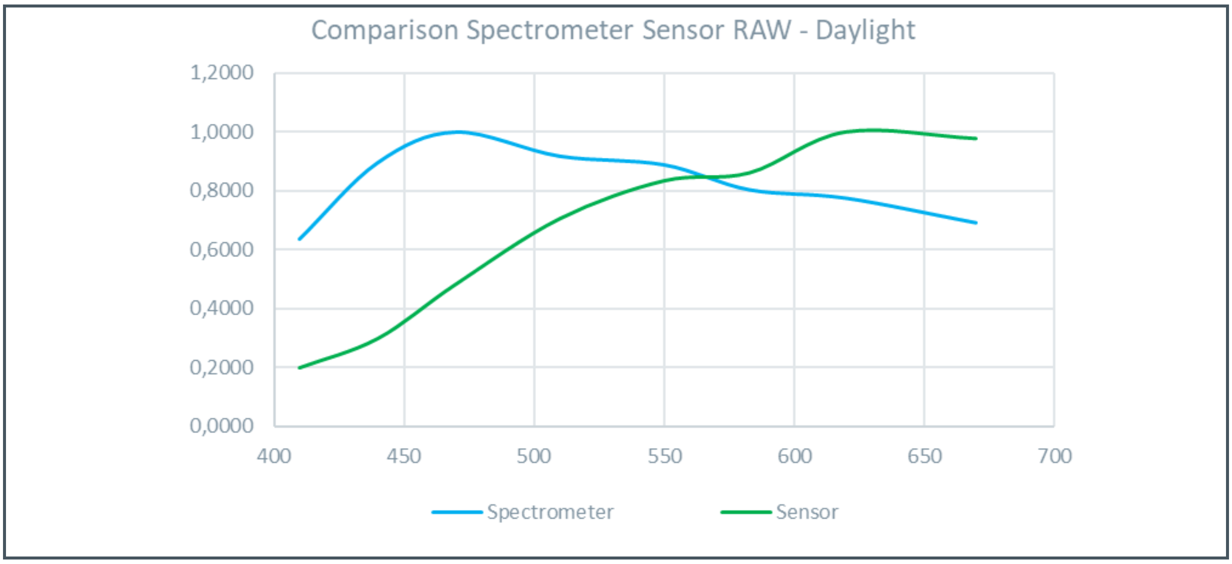
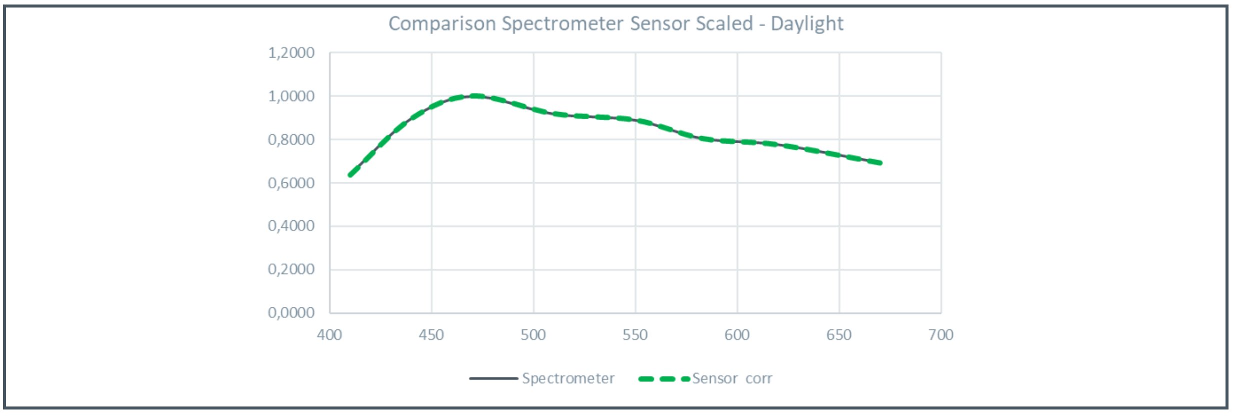


Figure 10:
Correction Factors Based on Daylight Scale (Spectrometer Values / Sensor Raw-Data)

	F1	F2	F3	F4	F5	F6	F7	F8
CorrFact	3.20	3.00	2.07	1.30	1.07	0.93	0.78	0.71

Figure 11 :
Comparison Spectrometer Results and Sensor Corrected Data for Daylight [1]



(1) Curves lie on top of each other.

Figure 12 :
Comparison Spectrometer, Sensor RAW and Sensor Corrected Data for LED Light

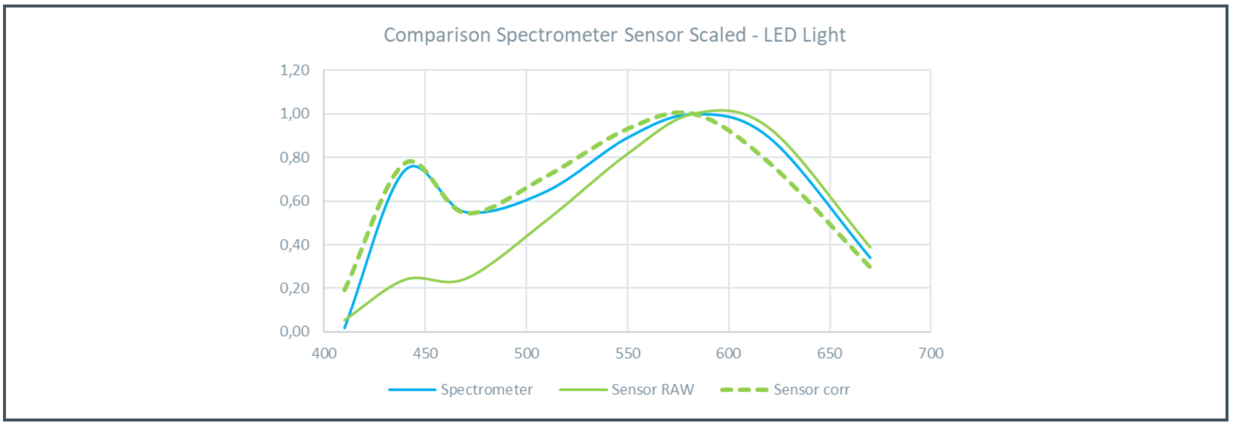
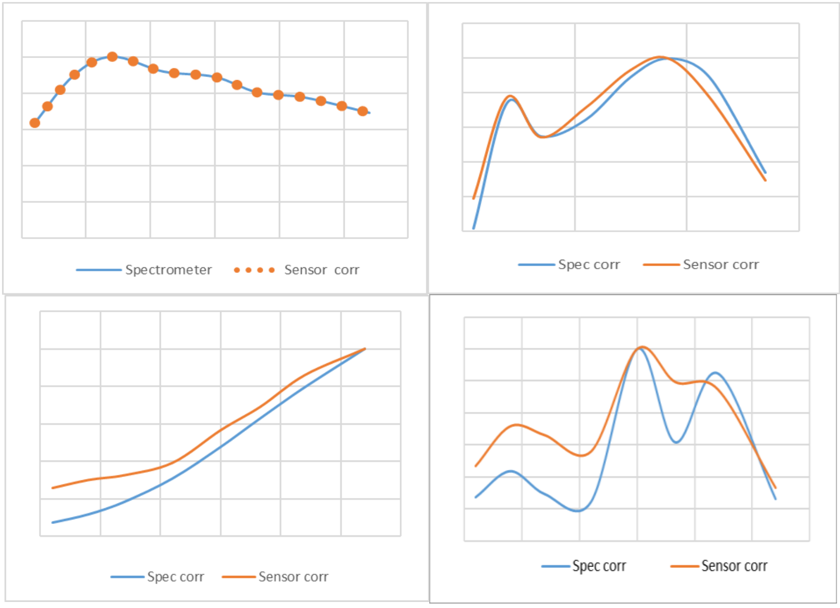


Figure 12 shows a comparison between the results of a spectrometer, Sensor RAW, and corrected data for an LED Light under the condition of using daylight for calibration. The Sensor corrected results (broken green) are much closer to the Spectrometer results than the unscaled results (green). The accuracy after correction for LED lighting is lower than for daylight because, for both corrections, a scaling based on daylight was used.

Figure 13:
Comparison Spectrometer Results, Sensor Corrected Results (based on daylight scaling) for Daylight, LED, A, CWF



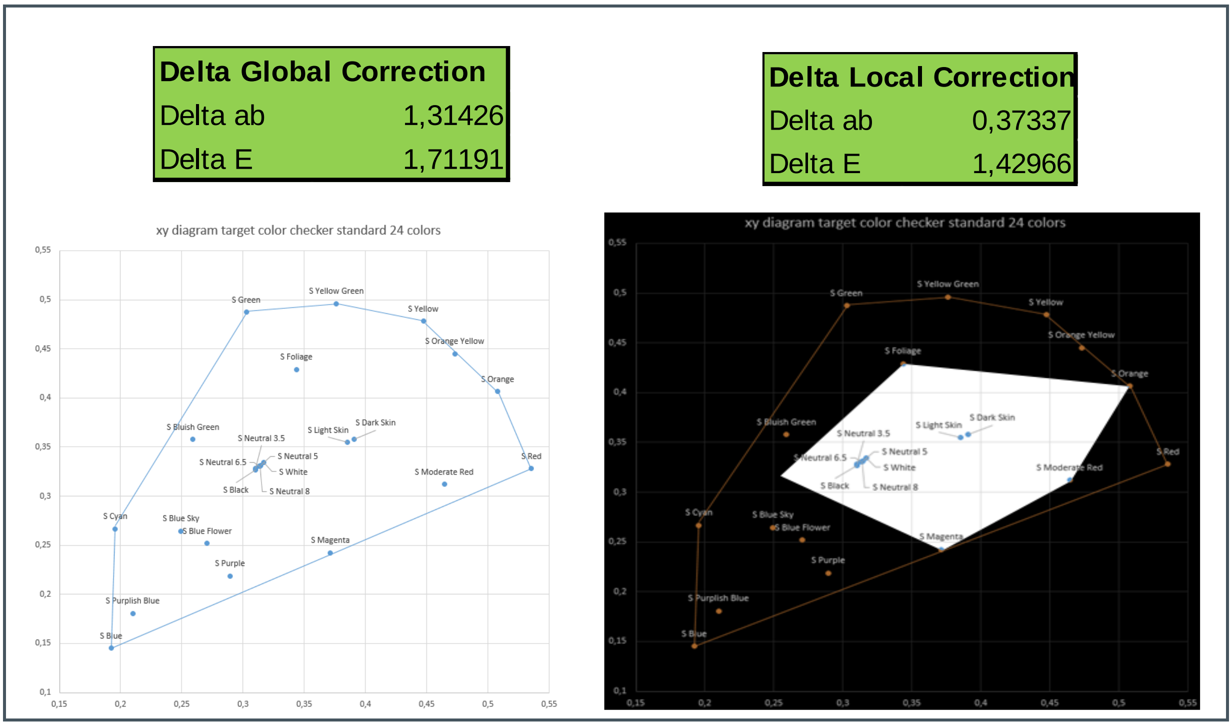
2.5 Calibration with Matrix Based Algorithm

Alternative calibration methods are used in case there are more than one or two reference values (white and/or black balance), which affect each other. Such an algorithm considers a relationship between n reference values = n targets T, measured with a reference device, and the Sensor results = values S (individual or typical) of the identical target. This relationship between T and S is described in a Calibration Matrix K - which represents a correction function that corrects and matches the Sensor results into the application-specific values measured with the reference device. It means such a method is corrected and matched in one-step. The target data determine the dynamics of the measuring range. That is not only a three-dimensional color space but also a reconstructed spectrum or others. Therefore, the matrix dimensions of the target and the algorithm must be matched.

If the target represents the entire dynamic range of the application, we are talking about a global target (e.g. the entire color space of natural colors) and a 'Global Correction' matrix. If the target represents only a small part of the application (e.g. only red colors as part of the entire color space), we speak of a 'Local Correction' and local correction matrix. However, a localized correction also only produces corrected results for this part of the target and is therefore only applicable to this smaller part. However, it can lead to better results under certain conditions, since the correction function has to consider fewer targets. Therefore, a two-step calibration can be advantageous if the global correction only determines the subspace in which one is located, then the local corrections are applied to this smaller part of the target. For example, a global color correction in CIE1931 RGB space is used to define an approximate position in the color space. Then, for example, a local matrix defined as 'red oriented matrix' can be used, which corrects 'red' more precisely (but does not take green as a color location into account).

Figure 14 shows for a color x (Dark Skin of the Color Checker), the comparison of the targets and results for the Global and Local Correction, if the target was reduced from 24 colors to 12, to the colors which have the smallest color distance Delta E around color x. The error in Delta ab can thus be reduced from 1.3 to 0.4 (or Delta E from 1.7 to 1.4) for the correction for this color x (Dark Skin).

Figure 14:
Comparison Results and Targets for 'Dark Skin' Global (Left) and Local Correction (Right)



The error here is always the deviation of the sensor values corrected by the matrix from the reference value (measured with a spectrometer).

It is important to make all measurements with the Sensor and reference device under identical conditions closed to the application. Each deviation from calibration and application decreases the accuracy.

The method of 'Linear Regression'[4] is often an algorithm, where the Calibration matrix values are determined from S and T.

The following formulas of Linear Regression with transposed and inversed matric calculations define Calibration Matrix K by using S and T:

[4] Alternative to 'Wiener Inverse'

Equation 12:

$$K = (T * S^T) * (S * S^T)^{-1}$$

Here, S = Sensor Values as Matrix (including Offset correction and based on Basic_Counts), T = Reference Values as Matrix and Target measurement from a Spectrometer, and K is the Calibration Matrix CM that can be used to correct and match Sensor results.

Figure 15 shows the general flow in the generation of the calculation of the matrix. From the point of view of calibration, the Sensor accuracy, as a result of calibration, is dependent on the calibration procedure, used targets (number, quality, relationship), as well as from the generation and validness of the relationship of Target (T) and Sensor results (S).

The algorithm and target must be adapted to the application and required accuracy and conditions of the sensing process. The number and quality of targets must represent the application-specific product. Targets can be optimized to get a minimum of deviation per target (as 'typical, min or max error' or averaged over all targets), compared with the reference device.

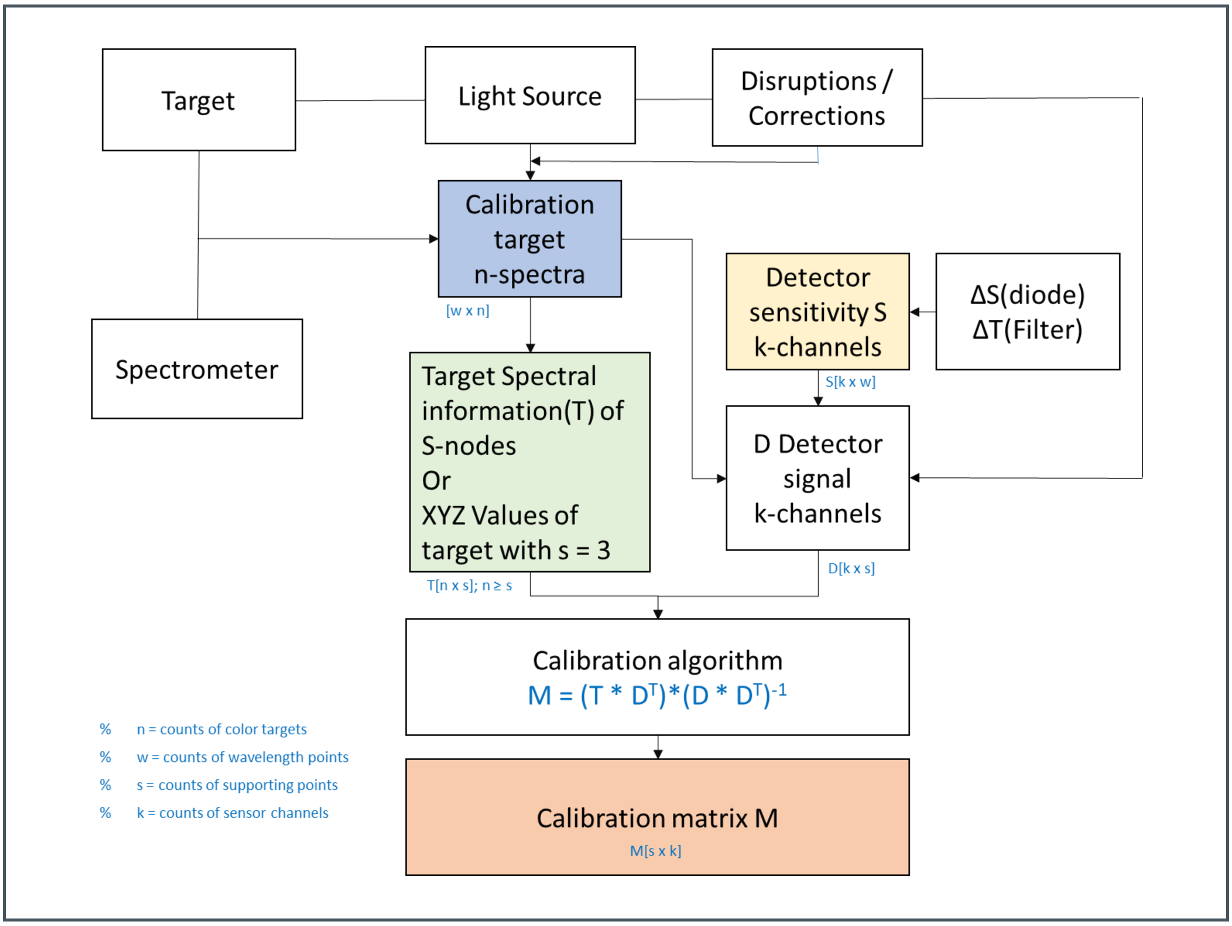
A calibration matrix can refer to a device-specific calibration, a GD[5]-batch calibration, or a GD-type calibration. It depends on which sensor data are used for calibration.

Device Calibration: This method is the most complex but has the highest accuracy. The targets must be measured separately with all the Sensors. Then, the data of each Sensor is compared with the reference data to get a device specific and individual calibration matrix. It is necessary if there are deviations between the individual Sensor systems or devices.

Batch Calibration: Here, the targets are captured with one Sensor from a batch and calculated with the reference data. The result is typical for all sensors in a batch. Therefore, this method is less complex, but does not take into account the individual deviations of the Sensors. It is recommended if there are only very small deviations between the individual Sensor systems in the batch.

[5] GD = Golden Device

Figure 15 :
Parts and Effects During the Process Calculation of Calibration Matrix



Type Calibration: Here, the targets are captured with a Sensor as a prototype and calculated with the reference data. The resulting calibration matrix is for all Sensors of this type, without consideration of the individual deviations or changes over time and all the batches. This method has the smallest effort but produces the worst results. Use this method in combination with a scaling where the individual deviations are corrected. In this case, the advantages can be used – the low effort of a Device-to-type calibration by a simple scaling to correct individual issues.

The GUI from the AS7341EVK was prepared to measure and correct the Sensor's data from luminaries[6] or in reflection mode[7].

For the luminary function, two alternative calibration matrices were prepared. The first matrix corrects the Sensor spectral values directly into CIE1931 XYZ values (Figure 16), the second interpolates and

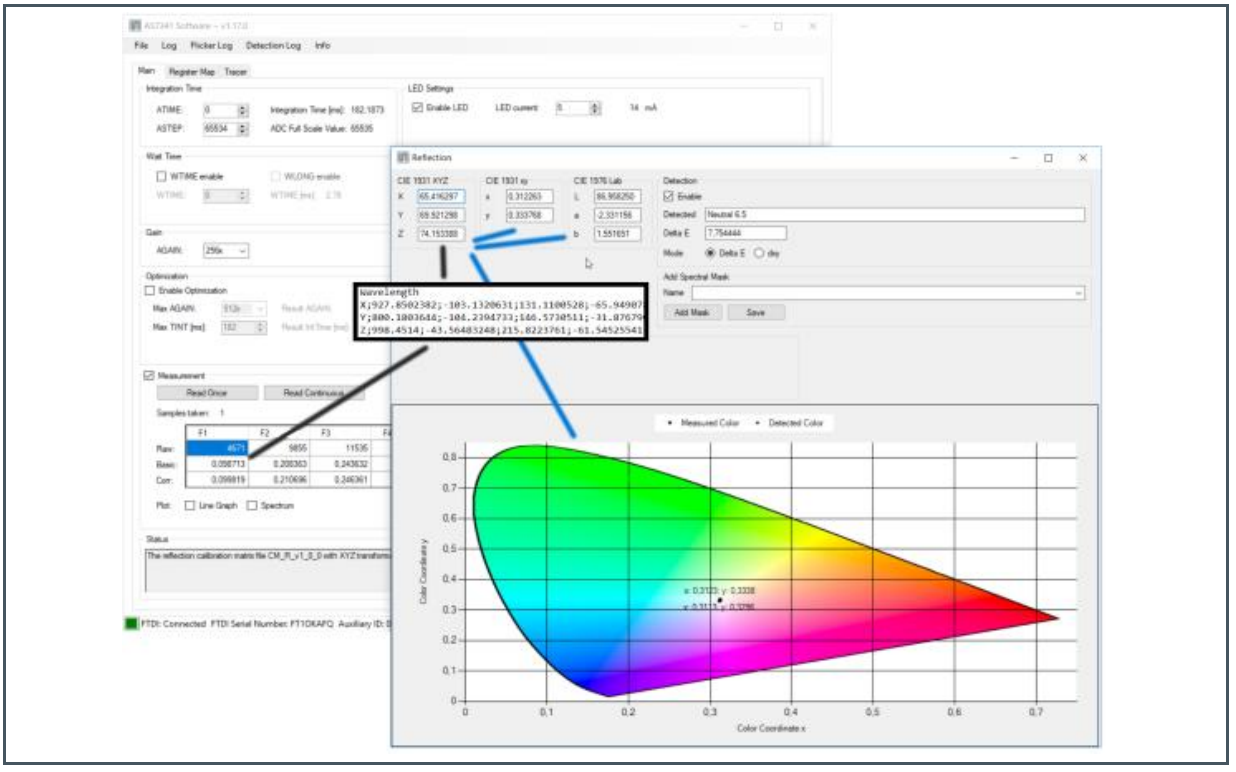
[6] For Ambient Light Sensing like detection CCT, lx, Lu'v' for D65, D50, A, CWF, TL84, LED, etc. by using a general calibration matrixes (CIE1931 XYZ and spectral reconstruction) = results of a type calibration what is valid for all typical light sources
[7] For using a general calibration matrix based on 24 Color of X-Rite Color Checker Large

generates a reconstructed spectrum with a step size of 1 nm (Figure 17). A spectrum evaluates itself, allows a spectral fingerprint, or works with CIE1931 XYZ quantities after XYZ mapping.

The following figures show the AS7341 GUI for both modes, from ‘Basic_Counts to the corrected values via Offset, scaling, and calibration by Matrices’.

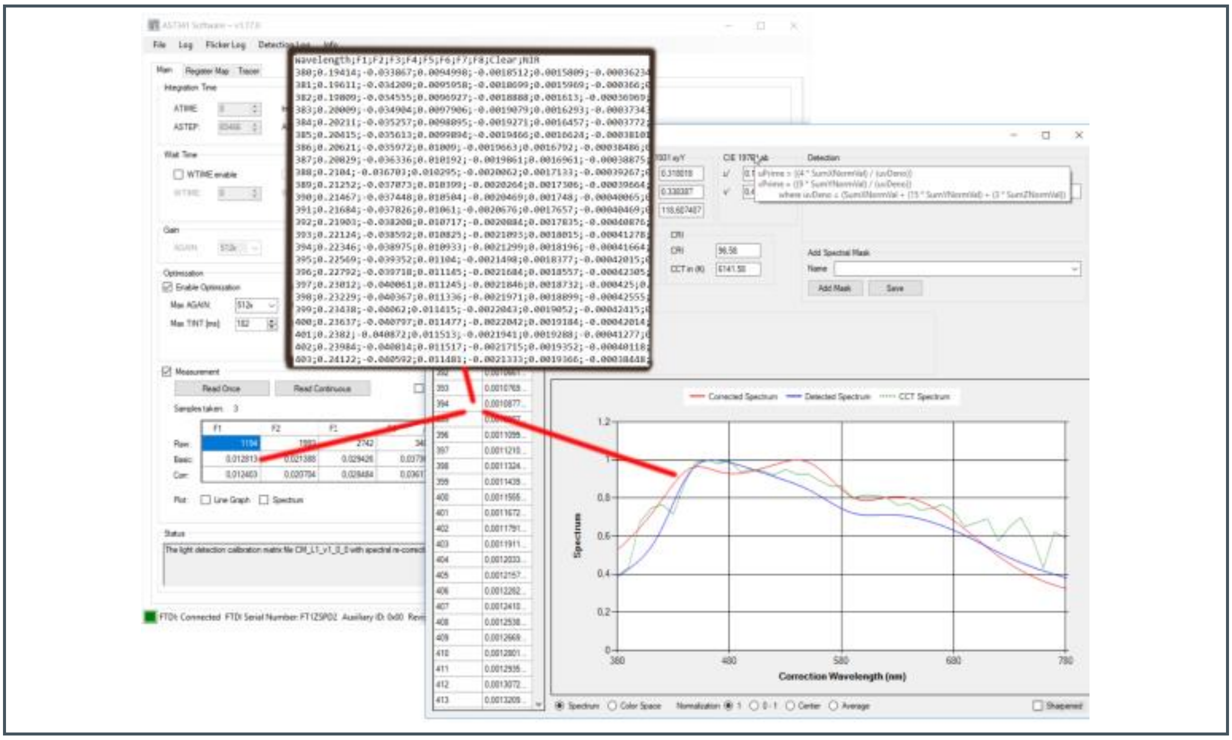
Depending on the mode and the deposited calibration matrix (see marked black boxes in Figure 16 and Figure 17), Raw_Counts are transformed by the calibration into a spectrum (then spectrum into XYZ) or direct into XYZ.

Figure 16 :
Basic_Counts to XYZ Values Based on XYZ Calibration (1)



(1) Filter names in GUI and in initialization files can vary based on different GUI versions.

Figure 17 :
Basic_Counts to XYZ Values Based on Spectral Calibration (1)



(1) Table for Calibration matrix interrupted. See the original spectral CM file after the EVK installation.

In the following subchapters, two Excel sheets show typical processes for calculating and using calibration matrices. The algorithm and data are identical to the AS7341 GUI, whose matrix usage is described above.

2.5.1 Example Reflection Mode

The first excel sheet[8] is an example of reflection mode. It shows the calculation and usage of a Spectral to XYZ based Global Calibration matrix[9]. The matrix calculation considers 24 measured reference targets from the Color Checker[10], measured with the Sensor (raw spectral values) and reference device (in XYZ values).

Figure 18 shows a part of the excel sheet where the reference values (Target T) from a spectrometer are listed as XYZ, and the Sensor values (S) and Offset are listed as corrected Basic_Counts per channel in rows. In the table, 24 columns include the 24 color targets.

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[8] Ask the **ams** support team for the original XLS file "*#Template Spectral to TCS Sensor calibration Refl.xlsx*" to check the data and formulas of the AS73XX.
[9] Example for local calibration on request.
[10] https://www.xrite.com/categories/calibration-profiling/colorchecker-targets.

Figure 18 :
Part of Excel Sheet [(1)] with Target, Sensor Values and Sensor Offset [(2)]

			Action 1: Copy the Spectrometer XYZ values of the measured refer					
TARGET DATA T	Reference values	1	2	3	4	5	6	
(Reference Values)		Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	luish Green	ange
	X	11,22	36,35	16,9	10,93	24,56	30,76	
	Y	10,23	33,51	17,92	13,63	22,76	42,37	
	Z	7,15	24,55	33,54	7,13	43,25	45,05	

Offset Sensor	Offset	Sensor	Action 2: Copy the 'Basic Counts' of Offset into the Cells [C11:C18].
(e.g. Optical Overcrossing)	415	0,0037	
	445	0,0139	*Background of the calibration is a calculation of t measured with a sensor as sensor rawdata. The used in the future under the same conditions as i* ***to input values to understand the calculations***
	480	0,0064	
	515	0,0285	
	555	0,0302	
	590	0,0301	
	630	0,0407	
	680	0,0121	

			Action 3: Copy the Sensor 'Basic Counts' from the protocol log file					
Sensor Matrix S	Basic Counts	1	2	3	4	5	6	
		Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	luish Green	ange
	415	0,029	0,088	0,077	0,027	0,107	0,108	
	445	0,087	0,252	0,327	0,076	0,427	0,400	
	480	0,050	0,182	0,131	0,054	0,166	0,249	
	515	0,190	0,634	0,421	0,303	0,512	1,066	
	555	0,314	0,859	0,464	0,396	0,491	1,116	
	590	0,405	1,305	0,417	0,320	0,566	0,745	
	630	0,309	1,048	0,292	0,227	0,633	0,390	
	680	0,107	0,407	0,115	0,082	0,269	0,153	

(1) Tables were interrupted. See the full tables in the original MS Excel File.
(2) Filter names in spreadsheets and other sensor files can vary based actual development status.

Figure 19:
Used Target (Global) CIE1931 Color Space from Color Checker for Calibration in xy-Diagram

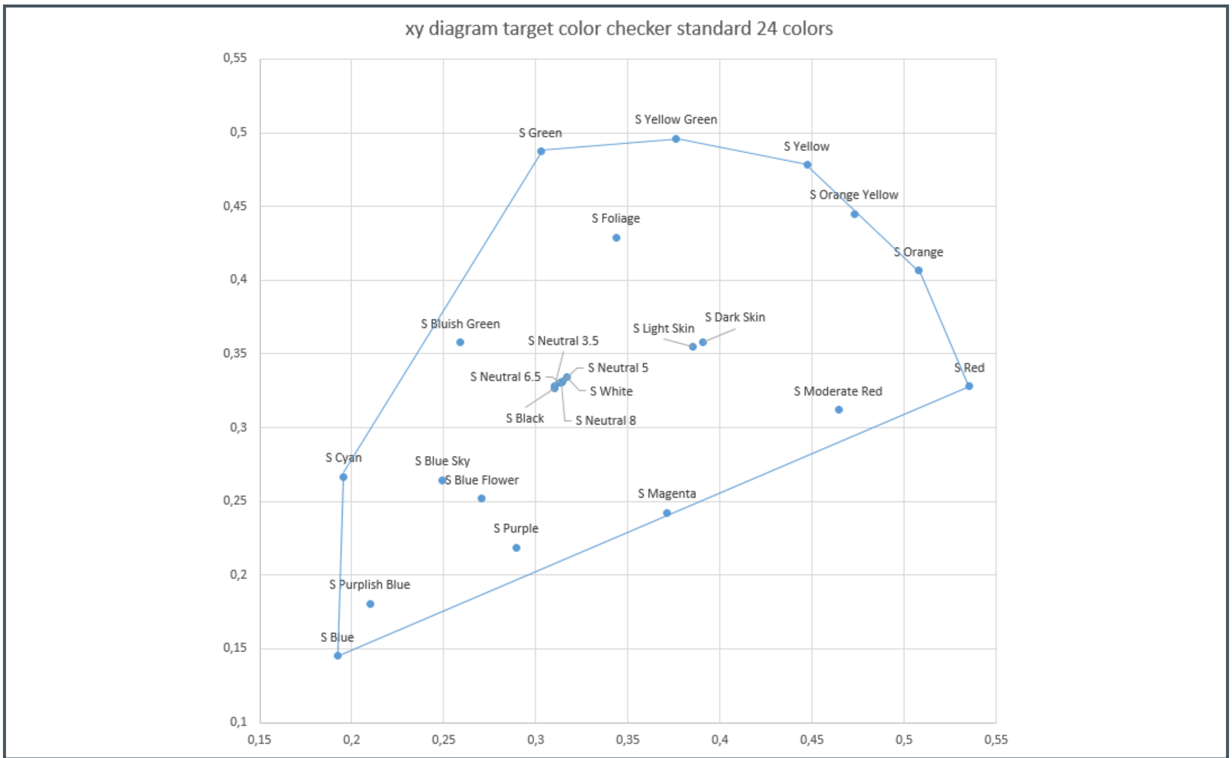


Figure 19 shows the used reference target 'Color Checker' (24 colors) in an xy diagram and represents the dynamic range of the sensor target. This means that all colors at an imaginary outer boundary line form in their sum, the color space, which is realized later by this correction. All colors in the color space can thus be included in the measuring range of the sensor. Colors outside the measuring range are not, or incorrectly, corrected. Fewer or more colors in the measuring range can increase/decrease the dynamic range of the sensor, if the color location changes the boundary lines. A change in the number of colors in the target usually leads to changed accuracies, both positive and negative.

The target determines not only the accuracy and dynamics of a calibration. The targets will determine the form of output values also. Using XYZ based targets will result in XYZ sensor values after calibration. If the target reference values are in spectral form, e.g. 1nm step size, then the result is also a spectrum with a step size of 1nm.

The following example in XLS shows the calculation of a correction matrix K, using a linear regression algorithm based on a 24xtarget (dark skin, light skin, etc. - see the columns in the first lines of Figure 20). The reference values of this target were measured with a spectrometer and the sensor values with a Multi-channel spectral sensor in RAW values of S. The correction matrix is calculated using matrix multiplications (inverse and transposed) of the sensor and reference matrix.

Customers can systematically verify the algorithms for calculating the calibration matrix in the XLS sheet to insert the algorithm into their software.

Figure 20 :
Part of Calculation of Direct XYZ Matrix based on Reference and Sensor Data (1)

Sensor Matrix corr offset S' = S - offset	Basic-Offset	Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	Bluish Gree	Orange Yell	Yellow Gree
	415	0,026	0,084	0,074	0,024	0,103	0,104	0,071	0,063
	445	0,073	0,238	0,313	0,062	0,413	0,386	0,107	0,109
	480	0,043	0,175	0,124	0,047	0,160	0,242	0,111	0,134
	515	0,161	0,605	0,393	0,275	0,484	1,037	0,605	0,978
	555	0,284	0,829	0,434	0,366	0,461	1,086	1,350	1,367
	590	0,375	1,275	0,386	0,290	0,536	0,715	1,665	1,033
	630	0,268	1,007	0,251	0,187	0,593	0,349	1,131	0,570
	680	0,095	0,395	0,103	0,070	0,257	0,141	0,405	0,227
Calculation: Matrix for linear transformation CM	A = T * S'_trans	67,197	212,134	117,689	487,974	716,428	785,182	554,435	206,290
		69,061	219,038	123,399	524,119	755,390	790,918	542,426	202,059
		68,752	249,548	121,031	450,237	584,552	599,090	423,157	162,273
	B = [S' * S'_trans]^-1	9143,937	-1887,998	772,049	-177,796	-85,805	-88,149	-51,852	-283,612
		-1887,998	434,899	-356,178	82,478	-11,049	41,494	14,796	16,562
		772,049	-356,178	994,726	-248,824	143,994	-128,202	-2,768	131,171
		-177,796	82,478	-248,824	71,265	-45,716	38,745	-2,846	-34,572
		-85,805	-11,049	143,994	-45,716	37,298	-29,608	9,883	21,944
		-88,149	41,494	-128,202	38,745	-29,608	29,496	-15,955	1,018
		-51,852	14,796	-2,768	-2,846	9,883	-15,955	50,035	-98,000
		-283,612	16,562	131,171	-34,572	21,944	1,018	-98,000	265,505
		Action 4: See and use the calculated Correction Matrix.							
Calculated Correction Matrix	CM = A * B	93,354	3,256	-5,881	1,634	8,483	9,474	17,403	-20,620
		64,077	-7,336	13,801	16,200	13,837	2,913	11,605	-21,562
		-23,483	99,493	40,677	3,939	-4,126	-0,391	-0,487	-3,863

(1) Tables interrupted. See the original Excel sheet for the full table.

The result of this sheet is the Calibration Matrix K, marked in green in Figure 20, which can be used to match the Sensor results after measuring the RAW data. This method of Linear Regression by using these data is only one example to get a correction matrix. Other algorithms are known and must be tested to get optimized sensor results.

Another method, which was shown earlier in this document, is to use a multi-stage matrix-based calibration concept, by mixing the methods one after another. For example, use a complete (global) color target (e.g. 24 colors) for calibration as a first step to get a local position in the CIE1931 color space, and then a local calibration around this color position, with a reduced color (selected 12 colors) target but higher accuracy.

Using a specific calibration matrix for each Sensor separately is a Device-specific calibration. If the matrix is used for an alternative Sensor from the same batch/for this specific product, then it is a batch-/type calibration. The calibration method, algorithm, and target must be harmonized with the application and its requirements.

The offset from Figure 18 and the Calibration Matrix from Figure 20 should be used as input data for the AS7341 GUI and Reflection Mode. For more details, see the manual for EVK.

Figure 22 shows the usage of the Calibration Matrix in comparison with the reference values. The formula can be checked systematically. It considers the calculation of the XYZ Tristimulus result for the Sensor, xy coordinates and the actual La*b* (D65 illumination, 2° observer). Deviations are given by comparison with the reference values.

In Figure 21, all results are present in one diagram. It can be seen that each color has its accuracy after the calibration. Therefore, the minimum, maximum, and average (typical) deviation of the color target is always interesting. Accordingly, calibration can be optimized to minimize color variations or min/max/typ. for a range of colors

Figure 21 :
Delta E after Correction, Using Direct XYZ Device Calibration

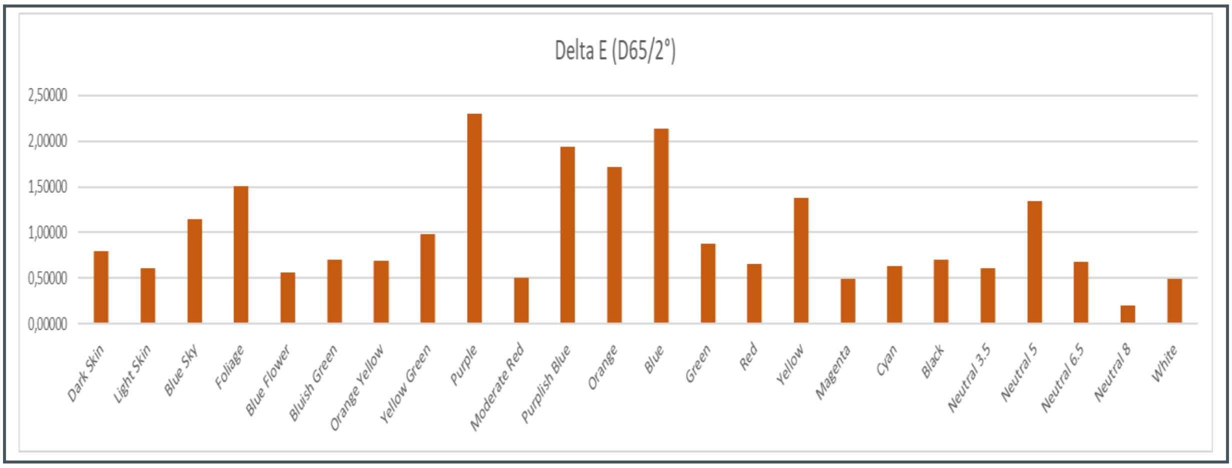
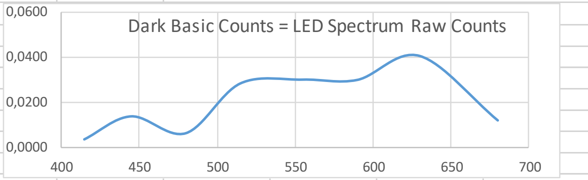


Figure 22 :
Using 24 Targets(1) to Correct Sensor Results and Comparison with References

Sensor Values and Results

Sensor Values	
Offset	‹ Basic Counts
415	0,0037
445	0,0139
480	0,0064
515	0,0285
555	0,0302
590	0,0301
630	0,0407
680	0,0121

Action 2: Copy the 'Basic Counts' of Offset into the Cel



Action 3: Copy the Sensor 'Basic Counts' from the prot

Sensor Values	1	2	3	4	5	6	7
Basic counts	Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	Bluish Green	)range Yellow
415	0,02948	0,08753	0,07736	0,02741	0,10674	0,10792	0,07495
445	0,08678	0,25168	0,32701	0,07578	0,42676	0,39957	0,12075
480	0,04986	0,18179	0,13060	0,05357	0,16627	0,24859	0,11736
515	0,18989	0,63372	0,42114	0,30315	0,51243	1,06551	0,63308
555	0,31438	0,85895	0,46402	0,39605	0,49125	1,11608	1,37982
590	0,40503	1,30530	0,41656	0,32049	0,56569	0,74547	1,69494
630	0,30905	1,04787	0,29192	0,22727	0,63343	0,38996	1,17124
680	0,10734	0,40668	0,11507	0,08183	0,26913	0,15322	0,41703

Corrected counts	Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	Bluish Green	range Yellow
415	0,02576	0,08381	0,07364	0,02369	0,10302	0,10420	0,07123
445	0,07286	0,23775	0,31308	0,06186	0,41283	0,38564	0,10683
480	0,04342	0,17535	0,12416	0,04713	0,15983	0,24215	0,11092
515	0,16137	0,60521	0,39263	0,27464	0,48392	1,03699	0,60456
555	0,28416	0,82874	0,43380	0,36584	0,46104	1,08586	1,34960
590	0,37494	1,27522	0,38647	0,29041	0,53561	0,71538	1,66486
630	0,26836	1,00718	0,25123	0,18658	0,59274	0,34927	1,13055
680	0,09520	0,39455	0,10294	0,06970	0,25700	0,14108	0,40490

Calibrated Results	Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	Bluish Green	Orange Yello
X	11,32	37,06	17,40	10,25	24,81	30,41	45,88
Y	10,42	34,21	18,32	12,73	22,89	42,11	43,02
Z	7,23	25,27	33,56	6,61	43,67	44,38	7,52
x	0,39083	0,38386	0,25113	0,34628	0,27155	0,26015	0,47587
y	0,35959	0,35438	0,26447	0,43025	0,25055	0,36021	0,44619
z	0,24957	0,26176	0,48441	0,22347	0,47790	0,37964	0,07794

Diff XYZ

XSP-XS	-1%	-2%	-3%	6%	-1%	1%	1%
YSP-XS	-2%	-2%	-2%	7%	-1%	1%	1%
ZSP-XS	-1%	-3%	0%	7%	-1%	1%	4%

Diff xy

dxy	0,00241	0,00129	0,00455	0,00138	0,00084	0,00170	0,00164

Average dxy	0,00287
Min dxy	0,00021
Max dxy	0,01214

Lab results

Spektrometer							
L (D65/2°)	38,25210	64,57175	49,39893	43,69756	54,82426	71,12527	71,85934
a (D65/2°)	11,43062	15,64004	-0,73245	-14,17288	13,19162	-32,25669	14,73924
b (D65/2°)	12,84954	17,18788	-22,31491	22,31357	-24,90771	1,18557	68,31215

Sensor							
L (D65/2°)	38,57729	65,13169	49,88239	42,35960	54,96364	70,94629	71,56802
a (D65/2°)	10,75451	15,57349	-0,08978	-13,56698	13,68309	-32,78591	14,77548
b (D65/2°)	13,11603	16,97310	-21,50346	22,00004	-25,14127	1,61832	68,94041

Color	Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower	Bluish Green	range Yellow
Delta E (D65/2°)	0,79617	0,60340	1,14245	1,50185	0,56171	0,70667	0,69346

Max DeltaE	2,30337
Min Delta E	0,19500
Average DeltaE	0,98487

2,50000

(1) Tables were interrupted. See the full tables in the original MS Excel File.

2.5.2 Example Light Detection

In the second Excel sheet, all steps from the ADC Sensor values to the photometric results in light detection, are shown based on two alternative calibration methods – ‘reconstructed spectrum’ and ‘direct XYZ matching’. Both methods are also part of the GUI. The following figure shows the used processes of the alternative methods as a block diagram.

In spectral reconstruction, the calibration matrix CM for light detection is a spectral matrix with a step size of 1nm, within the wavelength 400 nm to 1000 nm. The calibration then yields a reconstructed spectrum in the given wavelength, which can be used for an XYZ calculation by multiplying the reconstructed spectrum and the CIE1931 standard observer function XYZ.

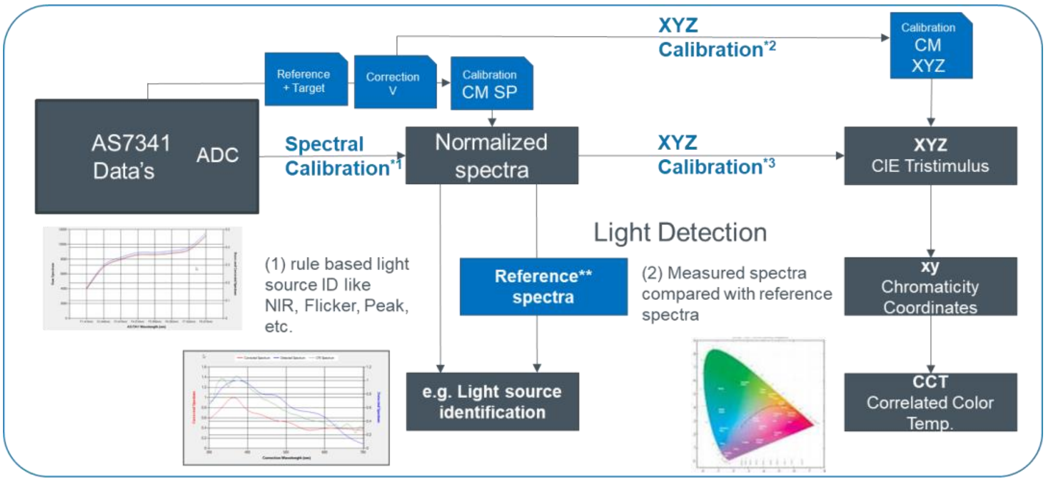
If XYZ calibration is used, the target must be a reference between the sensor ADCs and the reference values measured with a spectrometer. The results after calibration are direct XYZ values for the actual measurement.

The calibration matrices for both variants were created with a ‘Golden Device GD’ sensor selected with a typical sensitivity. The sensor was stimulated with typical light sources and referenced with the spectrometer results to the calibration matrices representing device-to-type calibrations.

Since all the sensors have deviations from this GD, all the sensors must be adapted or scaled to the GD. A scaling to daylight or another homogeneous light spectrum can do this.

The results of the calibration for light detection are XYZ photometric values that can be used to calculate Lu'v', CCT, and Lux. The use of spectral calibration also allows typical calculations based on spectral values such as CRI or advanced functions (e.g. light source detection by Spectral Mask Compare).

Figure 23 :
Alternative Calibration Process for 'Light Detection'



The following figures show a part of an Excel sheet with a calibration procedure based on the algorithms 'spectral calibration' and 'XYZ calibration'. The excel sheets explain all the steps for both algorithms - from spectral ADC calculated Basic_Counts, corrections, calibration, and XYZ calculations to get the photometric results. All formulas can be checked over the full algorithm systematic or are helpful to benchmark own software. Figure 24 shows the Sensor data from ADC as Basic_Counts, before/after corrections, and lists all correction values that can be used also direct in EVK GUI's ALS initialization and calibration files. For more details, see the manual for EVK. Figure 25 presents the process from 'reconstructed spectrum'[11] to 'photometric results'. Figure 26 contains the photometric result, but it is based on the direct XYZ calibration. The reason for the small differences between both photometric results is the different algorithms and calibration matrices despite the identical Sensor and reference targets in the calibration process.

Regardless of the small differences, both algorithms differ not only in the algorithms but also in the effort required to correct them. Depending on which filters are included in the calibration, the XYZ matrix for direct calibration has a dimension of [3x8…11]. The spectral reconstruction requires a matrix dimension of [400x8…11]. Since the matrices have to be stored and used in the microcontroller, this should be taken into account when selecting the method. On the other side, spectral reconstruction also offers greater flexibility and contains more information. Spectral results, such as CRI and spectral comparisons of light sources and perturbations, can be calculated via the spectrum, which is not possible via color coordinates. Thus, each application has to be adjusted and optimized regarding its necessary functions, accuracies, and effort in calibration.

[11] Based on a calibration file, which is inserted in another sheet. The calibration file is based on a General Calibration, which is described in chapter 2.5 of this document.

Figure 24 :
Sensor Data Plus Corrections are the Basics for Calibrations [(1)]

Measured Sensor's Channel Data's						switch on/off NIR correction ---v	
AS7341 Channel	Channel Wavelength (WV)	Basic Counts from protocol file	Basic Counts Gain Corrected	Corr Sensor Factor	Offset	NIR Corr On/Off	Corrected Sensor Data's
F1	415	0,011526	0,011057	1,00000	0,00000		0,011057
F2	445	0,020497	0,019664	1,00000	0,00000		0,019664
F3	480	0,029501	0,028302	1,00000	0,00000		0,028302
F4	515	0,033869	0,032492	1,00000	0,00000		0,032492
F5	555	0,036251	0,034778	1,00000	0,00000		0,034778
F6	590	0,035457	0,034016	1,00000	0,00000		0,034016
F7	630	0,041338	0,039658	1,00000	0,00000		0,039658
F8	680	0,044997	0,043168	1,00000	0,00000		0,043168
Clear	750	0,133147	0,127734	1,00000	0,00000		0,127734
NIR	900	0,054001	0,051806	1,00000	0,00000		0,051806

(1) Filter names in spreadsheets and other sensor files can vary based actual development status.

Figure 25 :
Reconstructed Spectrum [(1)] and Photometric Results after Spectral Reconstruction

Spectral Reconstruction based on Channel data's			Matching Spectrum into XYZ				CIE1931 based on Golden Unit Spectral Calibration Matrix		
WV	Reconstructed Sensor Spec	Reconstructed Sensor Spec Normalized	WV	X	Y	Z			
380	0,000849	0,482	380	0,000001	0,000000	0,000005	X	0,13598	
381	0,000858	0,486	381	0,000001	0,000000	0,000006	Y	0,14678	
382	0,000867	0,491	382	0,000001	0,000000	0,000007	Z	0,17377	
383	0,000876	0,496	383	0,000002	0,000000	0,000007	x	0,29786	
384	0,000884	0,501	384	0,000002	0,000000	0,000008	y	0,32151	
385	0,000893	0,506	385	0,000002	0,000000	0,000009	z	0,38063	
386	0,000902	0,511	386	0,000002	0,000000	0,000011			
387	0,000911	0,517	387	0,000003	0,000000	0,000012	Lx	100	lx
388	0,000921	0,522	388	0,000003	0,000000	0,000014	L	1,33	
389	0,000930	0,527	389	0,000003	0,000000	0,000016	u'	0,19026	***
390	0,000939	0,532	390	0,000004	0,000000	0,000019	v'	0,46206	***
391	0,000949	0,538	391	0,000005	0,000000	0,000021			
392	0,000958	0,543	392	0,000005	0,000000	0,000024	CCT	7478	K
393	0,000968	0,549	393	0,000006	0,000000	0,000027	CCT outside range		
394	0,000978	0,554	394	0,000007	0,000000	0,000031			
395	0,000988	0,560	395	0,000008	0,000000	0,000036	*** for 2° observer and illuminant C		

(1) Tables were interrupted, see the full tables in the original MS Excel File.

Figure 26 :
Photometric Results After XYZ Calibration

CIE1931 based on Golden Unit XYZ Calibration Matrix		
X	0,13498	
Y	0,14594	
Z	0,17119	
x	0,29856	
y	0,32279	
z	0,37865	
Lx	100	lx
L	1,32	
u'	0,19027	***
v'	0,46287	***
CCT	7413	K

Calibration is therefore dependent on the method, the target, disturbances, sensor settings, and results. If necessary, several methods may have to be applied, one after the other. The following figure shows general sensor results after calibration of different light sources for matrix-based methods.

- For (A), a general calibration matrix based on the design data of the filters,
- For (B), a general calibration matrix based on the measurement data from a typical sensor (golden device), and
- For (C), a general calibration matrix based on the measurement data from a typical sensor (golden device) with additional adjustment by scaling.

Figure 27:
Typical Results for Alternative Calibration Methods for ALS

		D65 Sensor		U30 Sensor		TL84 Sensor		CWF Sensor		IND A Sensor		HZ Sensor	
		Target	Measured	Target	Measured	Target	Measured	Target	Measured	Target	Measured	Target	Measured
(A) General Calibration	Spectral Compare	D65		U30		TL84		CWF		Ind A		HZ	
	CCT absolute	6514	7068	2898	3329	3922	4539	4040	4379	2884	3519	2365	3488
	Error abs and %	**554**	**9%**	**431**	**15%**	**617**	**16%**	**339**	**8%**	**635**	**22%**	**1123**	**47%**
	Lux absolute	1083	1057	1568	1550	1485	1175	1146	937	1802	1900	1124	1343
	Error abs and %	**26**	**2%**	**18**	**1%**	**310**	**21%**	**209**	**18%**	**98**	**5%**	**219**	**19%**
	Spectral Compare	D65		U30		TL84		CWF		Ind A		HZ	
(B) Golden Device Calibrated	CCT absolute	6514	7056	2898	3225	3922	4311	4040	4227	2884	2880	2365	2296
	Error abs and %	**542**	**8%**	**327**	**11%**	**389**	**10%**	**187**	**5%**	**4**	**0,14%**	**69**	**3%**
	Lux absolute	1083	1039	1568	1260	1485	1185	1146	963	1802	1710	1124	1050
	Error abs and %	**44**	**4%**	**308**	**20%**	**300**	**20%**	**183**	**16%**	**92**	**5%**	**74**	**7%**
	Spectral Compare	D65		U30		TL84		CWF		Ind A		HZ(CT	
(C) Golden Device Calibrated plus Balance	CCT absolute	6514	6787	2898	2835	3922	3836	4040	4180	2884	2837	2365	2238
	Error abs and %	**273**	**4%**	**63**	**2%**	**86**	**2%**	**140**	**3%**	**47**	**2%**	**127**	**5%**
	Lux absolute	1083	1072	1568	1445	1485	1365	1146	1041	1802	1752	1124	1035
	Error abs and %	**11**	**1%**	**123**	**8%**	**120**	**8%**	**105**	**9%**	**50**	**3%**	**89**	**8%**

2.5.3 Example Display Measurement

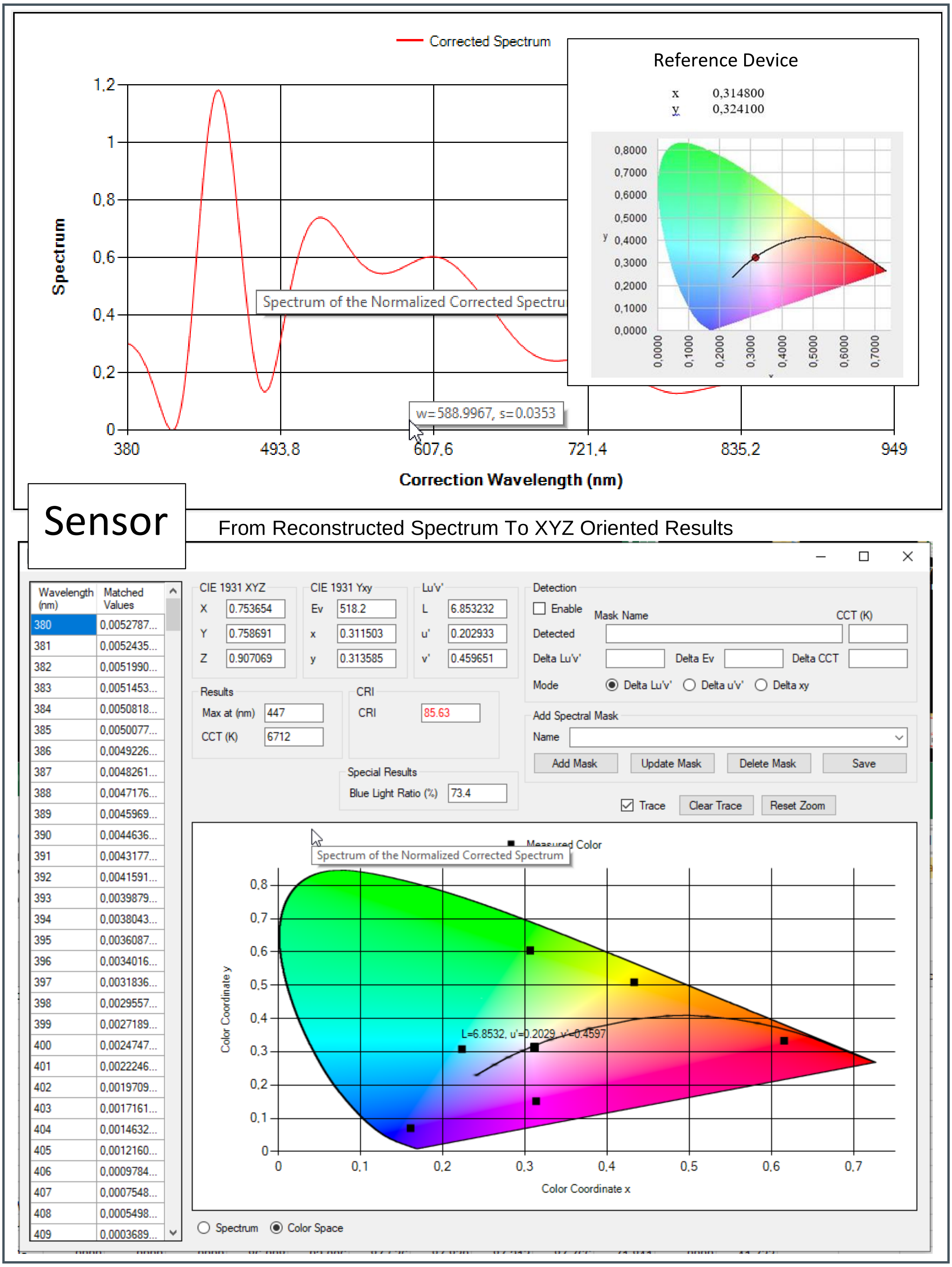
In the display measurement application, the ALS correction matrix (see chapter 2.5.2) should produce logically correct results (see Figure 28, e.g. Delta xy = 0,01) as a reconstructed spectrum or in CIE1931 color space.

In this cases and regarding GUI tests, no other correction matrix than the in standard installed matrix should be used. In case of using a Golden Matrix (lot or type calibration), a correction vector to adapt sensor raw counts to Golden Device or a White Balance can be helpful to increase accuracy.

Another way is using a direct spectral to XYZ correction matrix based on targets which are measured on display with sensor and reference device. It is the same procedure like described in chapter 2.5.1 but by using another target. **ams** provides templates in which calibration and correction are shown as examples.

Be attended to the number of linearly independent targets, which must be greater than or equal to the number of filters used in the sensor to obtain a stable matrix.

Figure 28:
Display Test Results in Color Diagram 'White' (by Using Trace Mode For Measured RGBWCMY)



3 Revision Information

Changes from previous version to current revision v2-00	Page
all chapters	all

- Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
- Correction of typographical errors is not explicitly mentioned.

4 Legal Information

RoHS Compliant & ams Green Statement

RoHS Compliant: The term RoHS compliant means that ams AG products fully comply with current RoHS directives. Our semiconductor products do not contain any chemicals for all 6 substance categories plus additional 4 substance categories (per amendment EU 2015/863), including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, RoHS compliant products are suitable for use in specified lead-free processes.

ams Green (RoHS compliant and no Sb/Br/Cl): ams Green defines that in addition to RoHS compliance, our products are free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material) and do not contain Chlorine (Cl not exceed 0.1% by weight in homogeneous material).

Important Information: The information provided in this statement represents ams AG knowledge and belief as of the date that it is provided. ams AG bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. ams AG has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. ams AG and ams AG suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

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