Application Note

AN000633

Spectral Sensor Calibration Methods

AS7341 EVK Evaluation Kit

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Content Guide

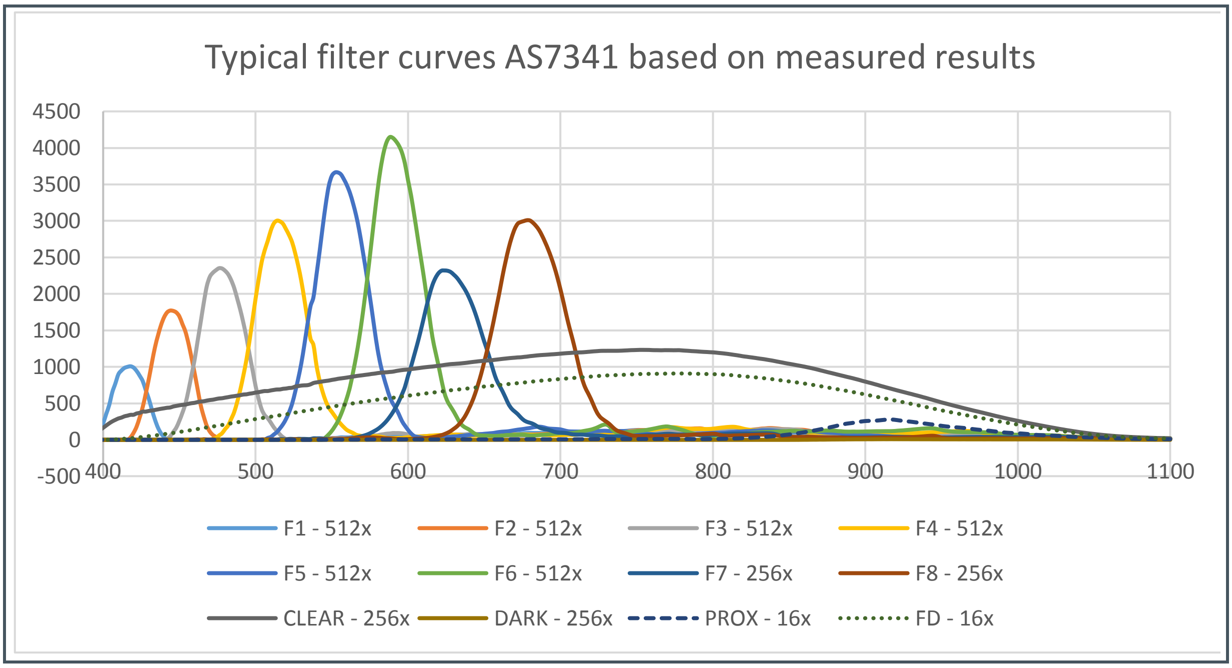
1 General Description

This Application Note describes how to implement correction and calibration methods by considering different effects based on the AS7341 EVK. It shows various steps, methods, and approaches used for alternative methods based on the AS7341 Eval Kits[1].

1.1 11-Channel Spectral Sensor AS7341

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

Figure 1 :
Spectral Behavior of Each Channels in AS7341[2]



The spectral filters give details about the measured spectrum. The Sensor results are depending on the Sensor setup and other direct effects like series-related disruptions and deviations. The results represent Sensor raw values as an overlapped response from diode sensitivity, filter, measured light

[1] See User Manual and Datasheet for more information. The AS7341 Kits are: AS7341 EVK and AS7341 EVK Reflection
[2] Measured with alternative gains

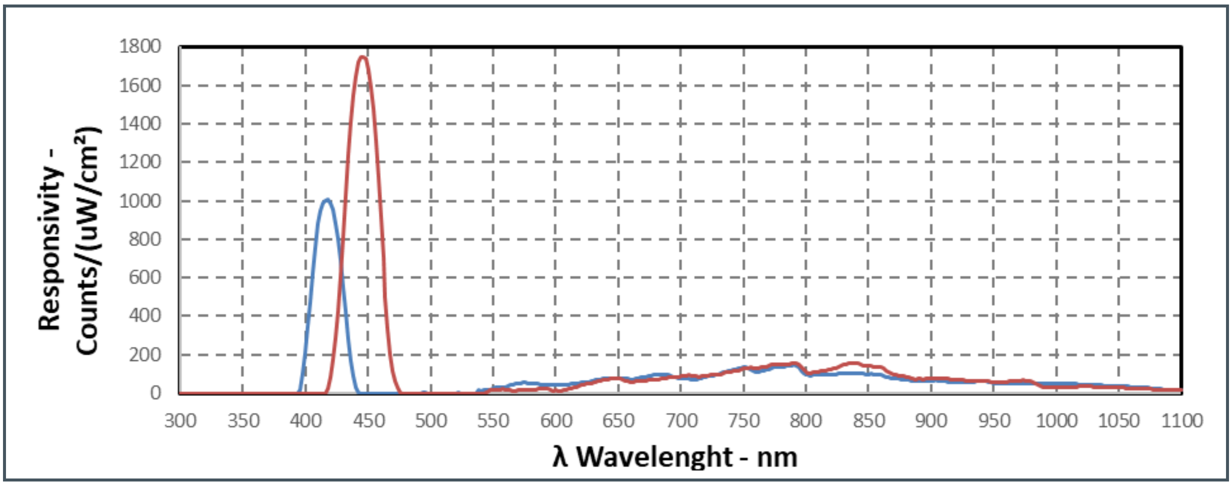
on the Sensor and occurring effects. In a final system setup, a correction of Sensor raw values is necessary to eliminate the unavoidable disturbing effects, and deviations.

The measured Sensor results as counts represent spectral characteristics as wavelength-related sensitivities in digital form (counts). The conversion of these counts into physical characteristics (the application) can occurs after the correction of the influences by curve fitting and can be part of the calibration.

Theoretical, 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, the filters overlap, which affects the filter channel results in transmission as an optical disturbance. Figure 2 shows the spectral response of filter 1 and 2, filter overlapping (doubled active filter in transmission). Correction factors during calibration will reduce such effects of these partially doubled reactions.

Further, it shows also that 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 optical channel band filters and can affect the Sensor results. Introducing an add-on blocker in the measurement setup cuts down this effect to a certain extent (e.g. rest-transmission in NIR blocked by an add-on NIR blocker) or specific algorithms are used in software to correct this issue (matrixing of rest-transmission in blocked VIS channels).

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



In addition to the potential causes of the filters, there are other system and application based influences of other Sensor components, which require a correction of the Sensor results.

1.2 Diffuser Compensation

The photodiodes inside AS7341 have a near cosine response to incoming light. Color 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.

Maximum angle of incidence to the photodiodes is limited to design requirements of the filter stack by the aperture / pin hole of the package. The rays with most obtuse angle hit the edge areas 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 AS7341 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 have always its own specific transmission curve which is greater zero and not constant. Therefore, correction of diffuser transmission may be required as one part within the calibration in the application level.

1.3 Other Disruptions

However, other disturbance variables influence the Sensor results statically or dynamically. In order to obtain optimum results, a verification and optimization process must correct and 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

See examples for such disturbances and corrections in the following pages.

2 Measurement Setup and Parameters for Measurement Accuracy

For Sensor applications, the measurement set and optical stability play a crucial role for accuracy and calibration. For the purpose of calibration, the most stable and reliable measurement set is selected. Monochromatic test systems and/or spectrometers are required as reference devices to study the target pattern, the behavior of light source and test setup. They are important to verify Sensor results. AS7341 reference devices should be active 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.

In general, test setup should be stable and free of any disturbances and drifts. On the other hand, effects and drifts must be checked individually and systematically for each application, possibly after adding modules, to obtain application typical or device-specific correction values.

In general, use the AS7341 Eval Kit for feasibility projects. Hardware, software, and adapters have been designed to be stable and ensure high accuracy for standard applications. However, the Eval Kits consists of bare hardware and is not shielded against any environmental conditions. The customer must do this as well as the application specific matchings. For more details, see the manual for the AS7341 Eval Kits.

3 General Correction

3.1 Calculations with BasicCounts

Sensor results are also depending on Sensor specific setup: the selected parameters for Gain AGAIN and Integration Time TINT. However, changing these parameters under constant conditions in a measurement should not change the real Sensor response. On the other side, ADC results are directly depending on and proportional to Gain and TINT and the higher Gain and TINT the better the ration between signal and noise. RAW counts from the ADC must be transformed into a result, which is not depending on the parameter setup but should achieve a maximum as possible. All Sensor calculations are on BasicCounts. The definition is:

Equation 1:

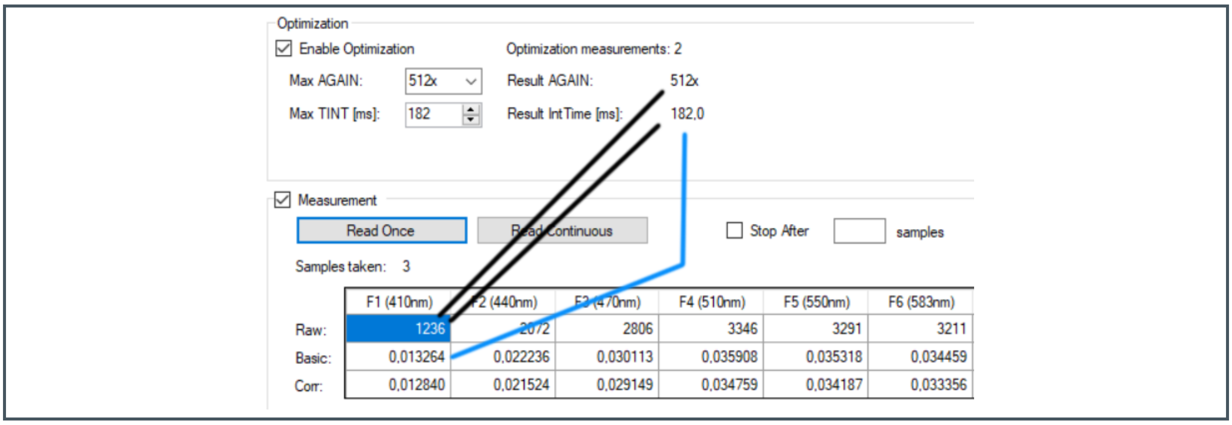
$$\text{BasicCounts} = \frac{\text{RawSensorValue}}{(\text{Gain} \times \text{Integration Time})}$$

Figure 3 shows an example from a protocol file with Setup, RawValues and BasicCounts.

The BasicCounts in this example for F1 are calculated by:

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

Figure 3 :
Example for BasicCounts from the AS7341 Eval Kit GUI



Use always BasicCounts for all corrections and calibrations, especially in case of changed setup of parameters during measurement series.

3.2 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 of the light source.

Each sensor channel has an own characteristically Offset. Therefore, consider individually Offsets per channel.

The first step of the correction is to measure the Offset. This requires often a special device setup. It is recommended to check more than one Sensor to see their individual deviations in Offset. Averaging can be a method to get an approximated and typical value for correction.

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

Equation 2:

$$\mathrm{SensorCorrectedValueOffset} = \mathrm{BasicCountSensor} - \mathrm{BasicCountOffset}$$

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

Figure 4 :
Example Calibration Files with Specified Offset and Factors for Corrections in AS7341 GUI

```
//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
```

3.3 NIR Correction

Figure 2 shows the transmission and rest transmission for two AS7341 filters (F1 + F2). Rest transmission affects the sensor results more or less, depending on NIR size and series tolerances. Therefore, NIR affects 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 not stable for measurements, then special situational methods are necessary.

The following pages show a method by 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 here presented method is based on the known proportions of the rest transmission of the F1...F8 filters in NIR 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.

The following input values are used:

From the sensitivity spectra ($S\lambda$ for all filters of AS7341 F1…F8, see Figure 1), the ratios between Fn and Clear filter at peak n (for F1 at 410nm etc.) and the sum of sensitivities for Fn in the wavelength [750…1100nm] compared with Clear filter [750…1100nm] are able to calculate. For general calibration, typical data's from a table (Figure 5) are used. For individual calibration, calculations from reconstructed sensitivity spectra can increase accuracy.

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 5:
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	1.8	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 NIR correction, first step is to balance the actual filter results F1…F8 (D_Basic – BasicCountSensor) by using Sλ_scaling factors. 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_Clear_NIR is the ratio between the balanced integral of Clear and filter channels F1 … F8 and represents the signal ratio in Clear and NIR.

Equation 6:

$$D\_Clear\_NIR_n = \left(D\_scale\_to\_Clearn_{Clear} - \sum_{k=1}^{8} D\_scale\_to\_Clearn_k\right) \quad / \, D\_scale\_to\_Clearn_{Clear}$$

D_F_NIR represents the NIR signal of Clear.

Equation 7:

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

NIR_weight is the calculated ratio of the Raw filters results of NIR and Clear.

Equation 8:

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

The formula Equation 9: corrects the measured value of the filters by the scaled portion of Clear in NIR.

Equation 9:

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

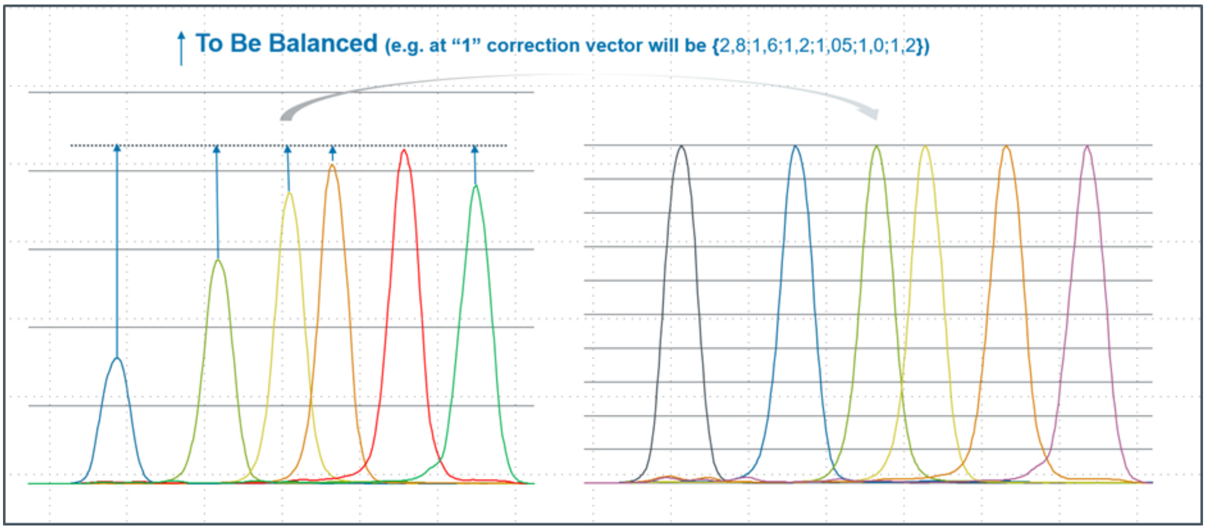
The results for filters Clear $D\_w_{n,Clear} = D\_scal_{n,clear}$ and NIR $D\_w_{n,NIR} = D\_scal_{n,NIR}$ does not change.

3.4 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 BasicCounts.

Figure 6 :
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 6).

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

Equation 10:

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

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 of 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 SensorCorrectedValueOffset and Xmin/Xmax are the two Reference Values min/max.

Figure 7 and followings show an example for scaling in a light application.

The example describes the light detection via spectral Sensor and inserts spectrometer target data (Figure 7), Sensor results as Sensor raw values and the corrected Sensor results after scaling (Figure 9).

The correction uses scaled 'Sensor values to spectrometer targets' for one defined light source – here used daylight. The result of scaling is the correction vector, which includes for each channel a value representing the deviation Sensor RAW to spectrometer (Figure 8). 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 quite good for such a primitive correction method but can be better using matrices. The difference between scale and matric methods are the numbers of used targets. A higher number of reference targets can increase accuracy for calibration dramatically.

Figure 7 :
Comparison Spectrometer Results and Sensor RAW Data for Daylight

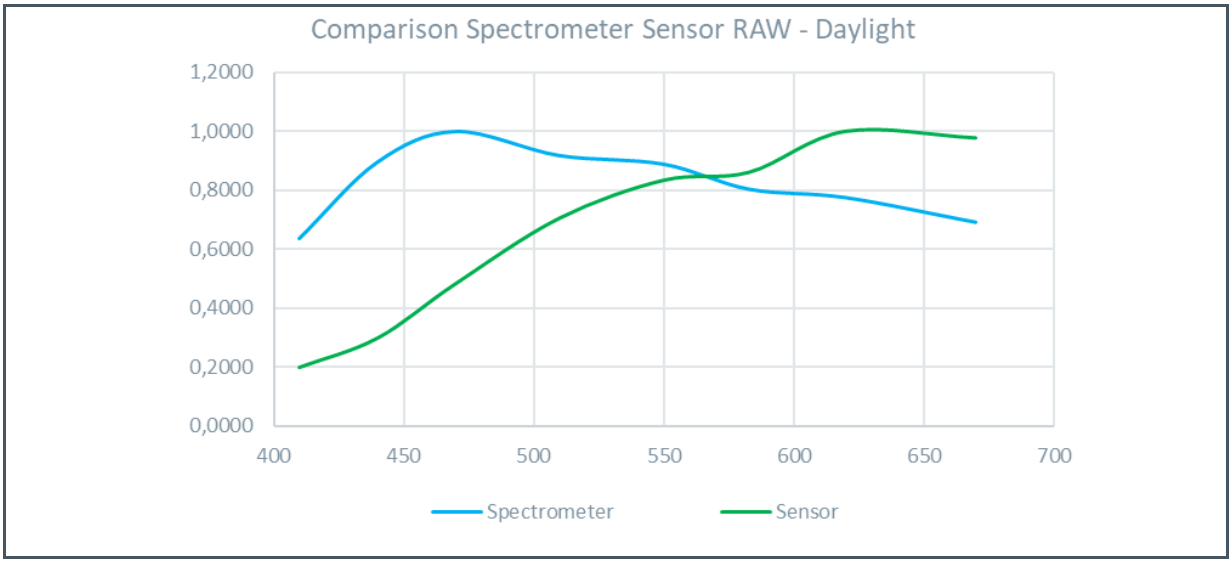
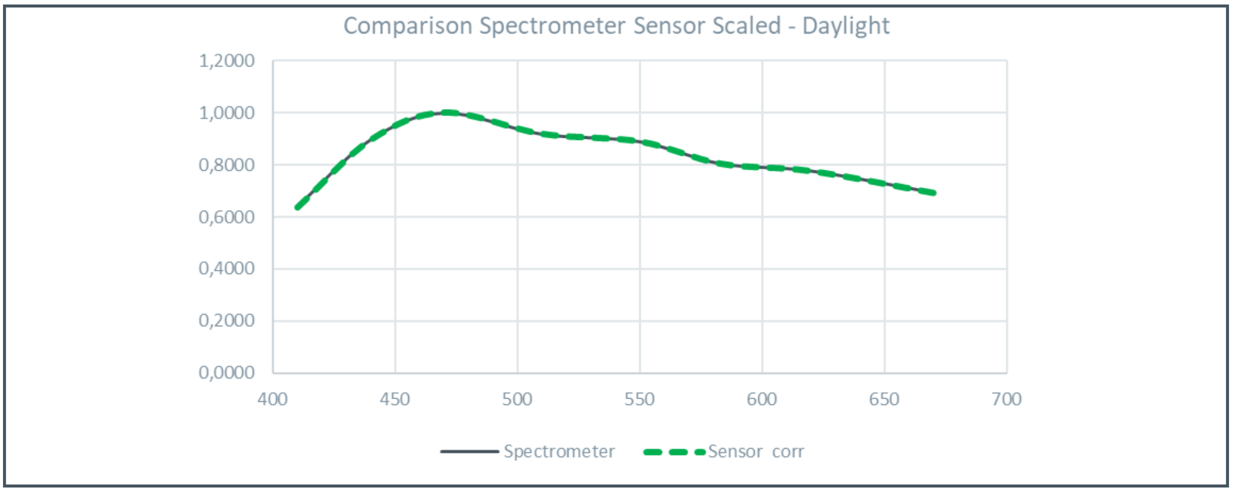


Figure 8:
Correction Factors Based on Daylight Scale (Spectrometer Values / Sensor Raw-Data)

	F1	F2	F3	F4	F5	F6	F7	F8
Filter nm	410	440	470	510	550	583	620	670
CorrFact	3.20	3.00	2.07	1.30	1.07	0.93	0.78	0.71

Figure 9 :
Comparison Spectrometer Results and Sensor Corrected Data for Daylight[3]



[3] Curves lie on top of each other

Figure 10 :
Comparison Spectrometer, Sensor RAW and Sensor Corrected Data for LED Light

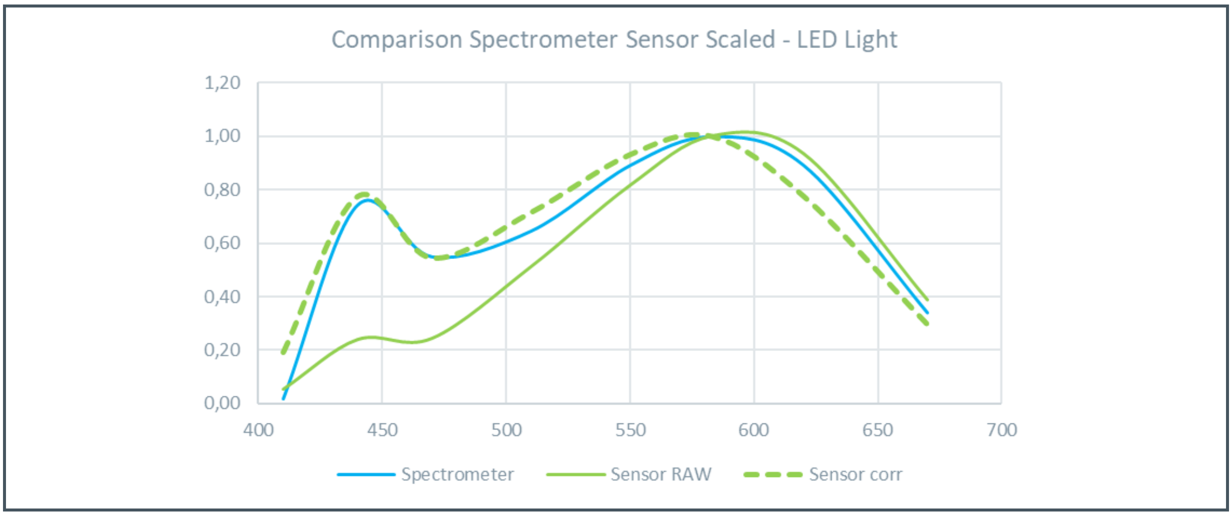
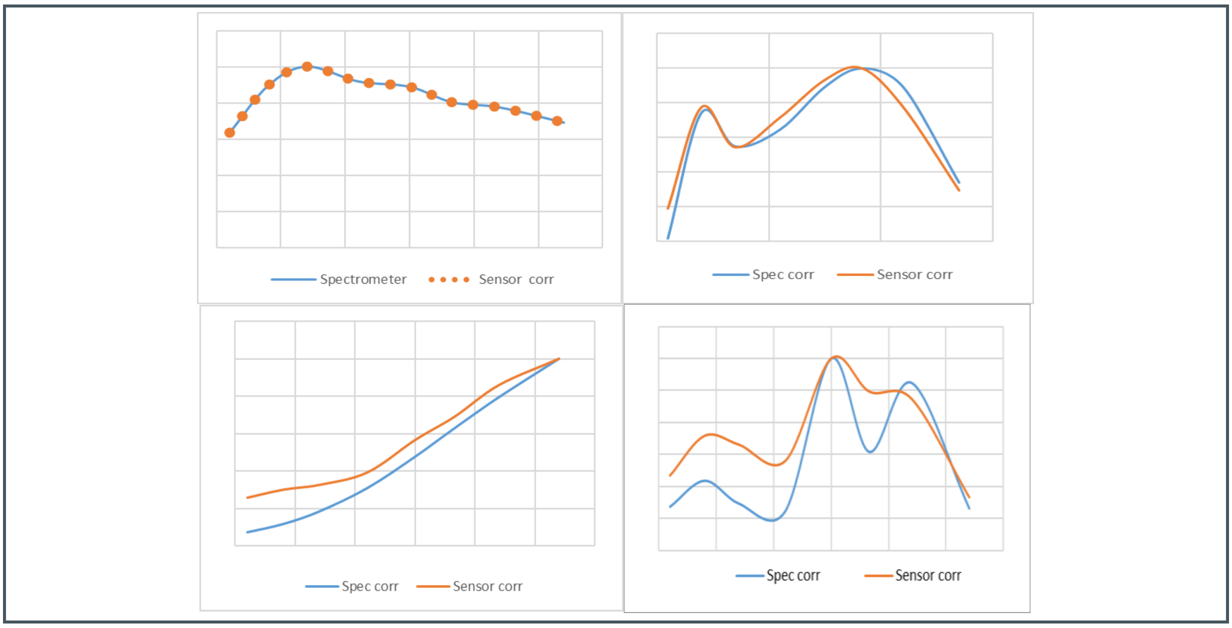


Figure 10 shows a comparison between the results of a spectrometer, Sensor RAW and corrected data for an LED Light under condition using daylight for calibration. The Sensor corrected results (broken green) are much closer to the Spectrometer results than the unscaled results (green). The accuracy after correction for LED lighting is lower than for daylight because for both corrections, a scaling based on daylight was used.

Figure 11:
Comparison Spectrometer Results, Sensor Corrected Results (based on daylight scaling) for Daylight, LED, A, CWF



3.5 Calibration with Matrix Inversion and/or Linear Transformation

Alternative calibration methods are in case there are more of one or two reference values, which affects each other. Such algorithm considers a relationship between reference values = target T, measured with a spectrometer and the Sensor results = values S (individual or typical) from the identical target. This relationship between T and S is described in a Calibration Matrix K what correct the Sensor results in the application.

Often the method of linear regression is an algorithm where the Calibration matrix values are determined from S and T. It is important to make all measurements with Sensor and reference device under identical conditions, which are closed to the application. Each deviation from calibration and application decreases the accuracy.

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

Equation 12:

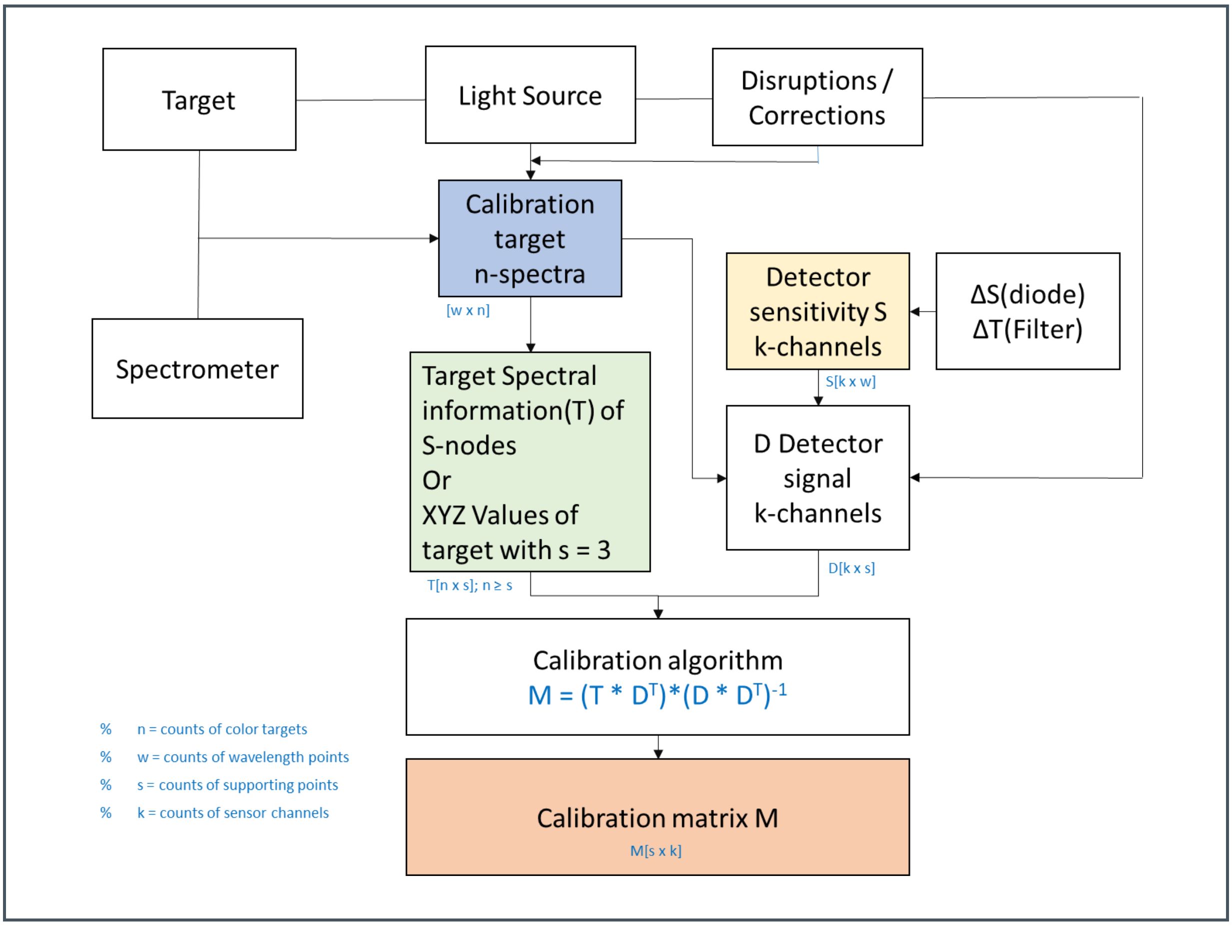
$$K = (T * S^T) * (S * S^T)^{-1}$$

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

Figure 12 shows the general flow of generation calculation matrix. From the point of view of calibration, the Sensor accuracy as result of calibration is depending on 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 sensing process. 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.

Figure 12 :
Parts and Effects During the Process Calculation of Calibration Matrix



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

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

Device-to-Batch: 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 individual deviations of the Sensors. It is recommended if there are only very small deviations between the individual Sensor systems in the batch.

Device-to-Type: 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 changings over time and over all 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.

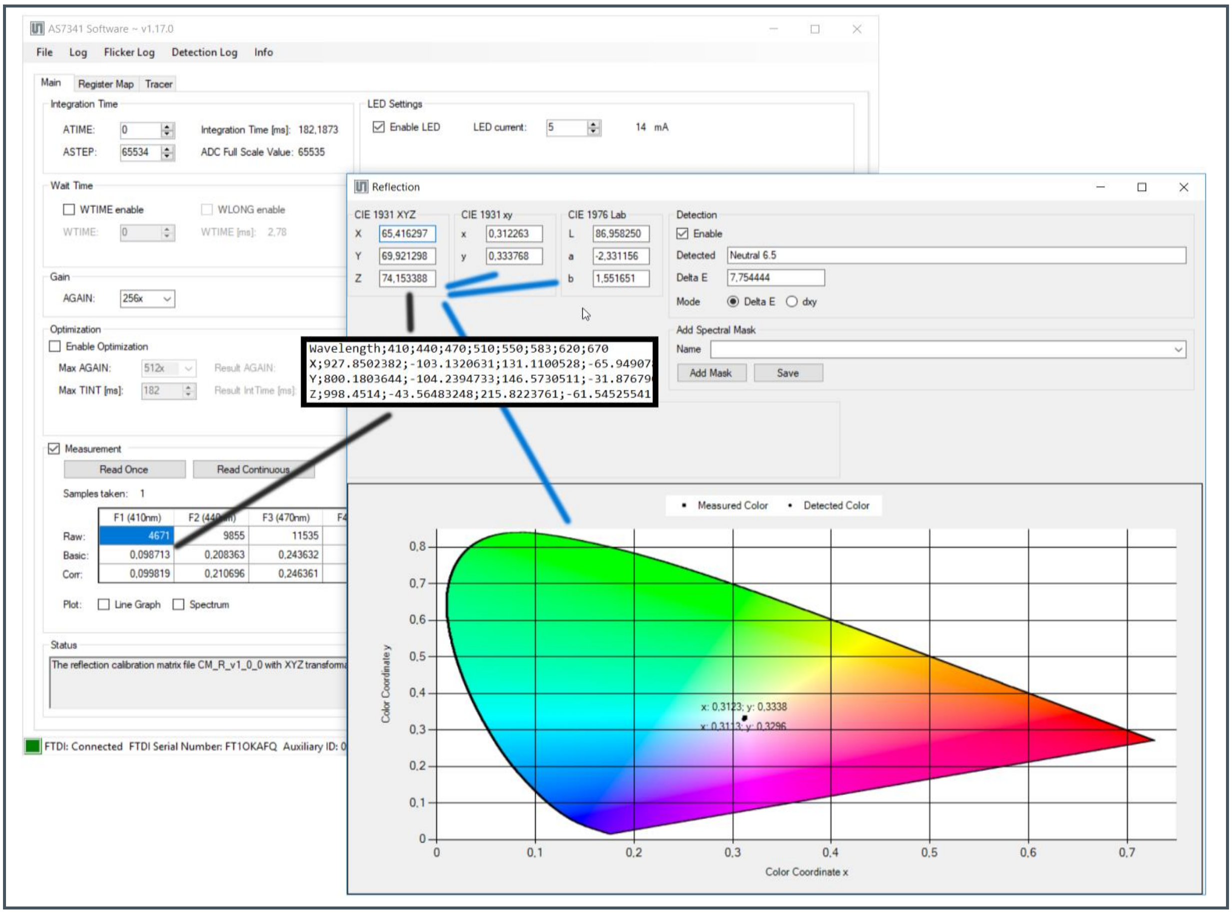
The GUI AS7341 from the EVK was prepared to measure and correct Sensor data's from luminaries[4] or in reflection mode[5].

For the luminary function, two alternative calibration matrices were prepared. The first matrix correct the Sensor spectral values direct into CIE1931 XYZ values (Figure 13), the second interpolates and generates a reconstructed spectra with a step size of 1nm (Figure 14). A spectrum allows to evaluate itself, a spectral fingerprint or to work with CIE1931 XYZ quantities after XYZ mapping.

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

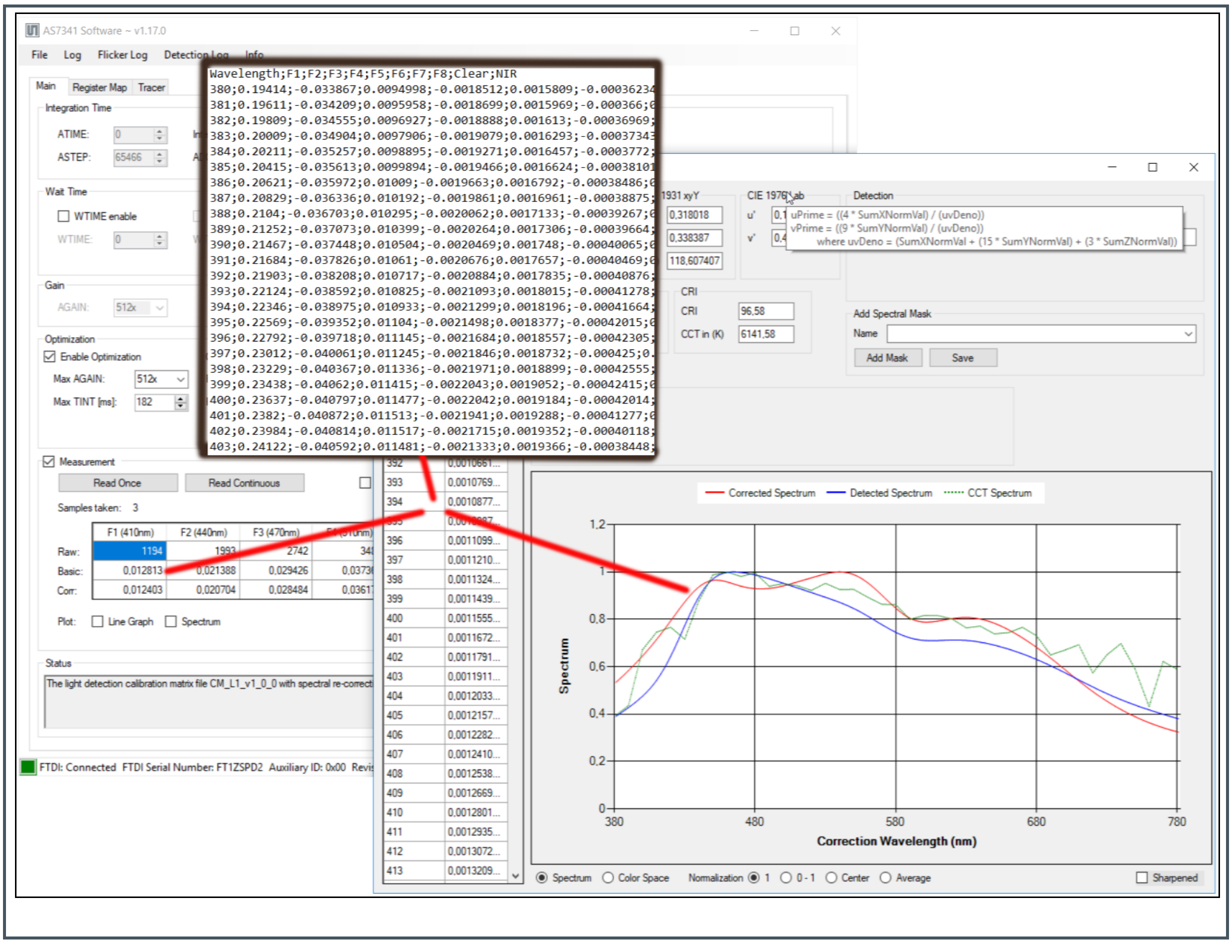
Depending on mode and deposited calibration matrix (see black marked boxes in Figure 13 and Figure 14), RAW counts are transformed by calibration into a spectrum (then spectrum into XYZ) or direct into XYZ.

Figure 13 :
BasicCounts to XYZ Values based on XYZ Calibration



[4] For Ambient Light Sensing like detection CCT, lx, Lu'v' for D65, D50, A, CWF, TL84, LED, etc. by using a general calibration matrixes (CIE9131 XYZ and spectral reconstruction) = results of a type calibration what is valid for all typical light sources
[5] For using a general calibration matrix based on 24 Color of X-Rite Color Checker Large

Figure 14 :
BasicCounts to XYZ Values Based on Spectral Calibration[6]



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

3.5.1 Example Reflection Mode

The first excel sheet[7] is an example of reflection mode. It shows the calculation and usage of an XYZ based Calibration matrix. The matrix calculation considers 24 measured reference targets from Color Checker[8], measured with Sensor and reference device.

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[6] Table for Calibration matrix interrupted, see the original spectral CM file after EVK installation
[7] Ask for the ams support team for the original XLS file '#Template Spectral to TCS Sensor calibration Refl.xlsx' to check data's and formulas AS7341
[8] https://www.xrite.com/categories/calibration-profiling/colorchecker-targets

Figure 15 shows a part of an excel sheet where the reference values (Target T) from a spectrometer are listed as XYZ and the Sensor values (S) and Offset are listed per channel in rows. In the table, 24 columns includes the 24 color targets.

Figure 15 :
Part of Excel Sheet[9] with Target, Sensor Values and Sensor Offset

Spectrometer		1	2	3	4	5
		Dark Skin	Light Skin	Blue Sky	Foliage	Blue Flower
Target data T	X	11,28	36,46	18,14	11,1	25,69
	Y	10,39	33,61	19,24	13,94	24,06
	Z	7,45	24,27	35,46	7,45	44,96
Sensor data S	WV	Dark Skin	Light Skin	Blue Sky	Foliage	lue Flower
	410	0,01816	0,04865	0,03595	0,01623	0,04626
	440	0,06717	0,16867	0,20743	0,05463	0,25168
	470	0,03445	0,10746	0,07917	0,03339	0,09249
	510	0,13624	0,39007	0,25942	0,18498	0,28215
	550	0,20168	0,50033	0,28164	0,23450	0,30353
	583	0,29249	0,83987	0,29377	0,22306	0,37725
	620	0,22079	0,67524	0,20517	0,15792	0,33522
	670	0,07529	0,24020	0,07839	0,05729	0,14056
Sensor offset	WV	off				
	410	0,00424				
	440	0,01765				
	470	0,00790				
	510	0,03488				
	550	0,03933				
	583	0,04509				
	620	0,04702				
	670	0,01739				

[9] Tables were interrupted, see the fully tables in the original MS Excel File

Figure 16 :
Calculation of Direct XYZ Matrix based on Reference and Sensor Data's[10]

Number of targets	**t**	**24**							
	target number	1	2	3	4	5	6	7	8
Spectrometer		**Dark Skin**	**Light Skin**	**Blue Sky**	**Foliage**	**Blue Flower**	**Bluish Green**	**Orange Yellow**	**Yellow Green**
	470	0,0266	0,0996	0,0713	0,0255	0,0846	0,1295	0,0630	0,0761
	510	0,1014	0,3552	0,2245	0,1501	0,2473	0,5707	0,3256	0,5545
	550	0,1623	0,4610	0,2423	0,1952	0,2642	0,5867	0,7051	0,7687
	583	0,2474	0,7948	0,2487	0,1780	0,3322	0,4416	1,0013	0,6686
	620	0,1738	0,6282	0,1582	0,1109	0,2882	0,2224	0,6909	0,3741
	670	0,0579	0,2228	0,0610	0,0399	0,1232	0,0824	0,2305	0,1357
	410	0,0139	0,0444	0,0317	0,0120	0,0420	0,0473	0,0418	0,0379
S" limited S for calibration	**440**	0,0495	0,1510	0,1898	0,0370	0,2340	0,2249	0,0707	0,0771
	470	0,0266	0,0996	0,0713	0,0255	0,0846	0,1295	0,0630	0,0761
	510	0,1014	0,3552	0,2245	0,1501	0,2473	0,5707	0,3256	0,5545
	550	0,1623	0,4610	0,2423	0,1952	0,2642	0,5867	0,7051	0,7687
	583	0,2474	0,7948	0,2487	0,1780	0,3322	0,4416	1,0013	0,6686
	620	0,1738	0,6282	0,1582	0,1109	0,2882	0,2224	0,6909	0,3741
	670	0,0579	0,2228	0,0610	0,0399	0,1232	0,0824	0,2305	0,1357
Target data limited for	**X**	11,28	36,46	18,14	11,10	25,69	31,32	45,97	35,43
calibration	**Y**	10,39	33,61	19,24	13,94	24,06	43,00	43,18	46,62
T	**Z**	7,45	24,27	35,46	7,45	44,96	45,70	8,36	12,18
		34,70	133,97	69,20	287,89	406,72	502,80	355,11	123,46
	A = T * S"_trans	35,79	138,83	72,63	310,11	431,09	510,07	350,14	121,55
		33,84	156,92	71,61	269,19	339,60	393,46	275,74	98,61
		47471,89	-5041,90	-2207,06	410,54	-1419,14	16,19	-186,86	-2440,44
	B = [S" * S"_trans]^-1	-5041,90	697,16	-466,28	89,85	70,11	59,37	25,58	165,54
		-2207,06	-466,28	3357,58	-701,22	498,77	-325,42	51,63	414,40
calculation:		410,54	89,85	-701,22	176,14	-135,07	90,42	-33,36	-58,22
matrix for linear		-1419,14	70,11	498,77	-135,07	142,69	-80,89	53,28	64,56
transformation K		16,19	59,37	-325,42	90,42	-80,89	74,67	-61,83	42,77
		-186,86	25,58	51,63	-33,36	53,28	-61,83	124,22	-207,29
		-2440,44	165,54	414,40	-58,22	64,56	42,77	-207,29	619,18
		379,79	-45,31	160,10	-40,47	36,46	-2,41	13,05	14,13
	K = A * B	275,70	-60,26	183,17	-9,18	44,38	-8,26	-2,22	20,43
		132,17	110,86	251,46	-37,90	17,82	-19,24	-15,47	38,38

In Figure 16 is the calculation of the Calibration Matrix based on the Linear Regression method. The algorithms to calculate the Calibration Matrix can be verified systematically. Formulas are in general form. The result of this sheet is the green marked Calibration Matrix K what can be used to match the Sensor results after measuring RAW data's.

Using this Calibration Matrix for this Sensor is a Device-to-device 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. Calibration method, algorithm, and target must be harmonized with the application and its requirements.

Offset from Figure 15 and Calibration Matrix from Figure 16 should be used as input data's for the AS7341 GUI for Pen Demo and AS7341 EVK Reflection mode. For more details, see the manual for AS78341 EVK GUI.

Figure 17 shows the usage of the Calibration Matrix in comparison with the reference values. The formula can be checked all systematically. It considers the calculation of XYZ Tristimulus result for the

[10] Tables interrupted, see the original Excel sheet for fully table

Sensor, xy coordinates and actual La*b* (D65 illumination, 2° observer). Deviations are given by comparison with the reference values.

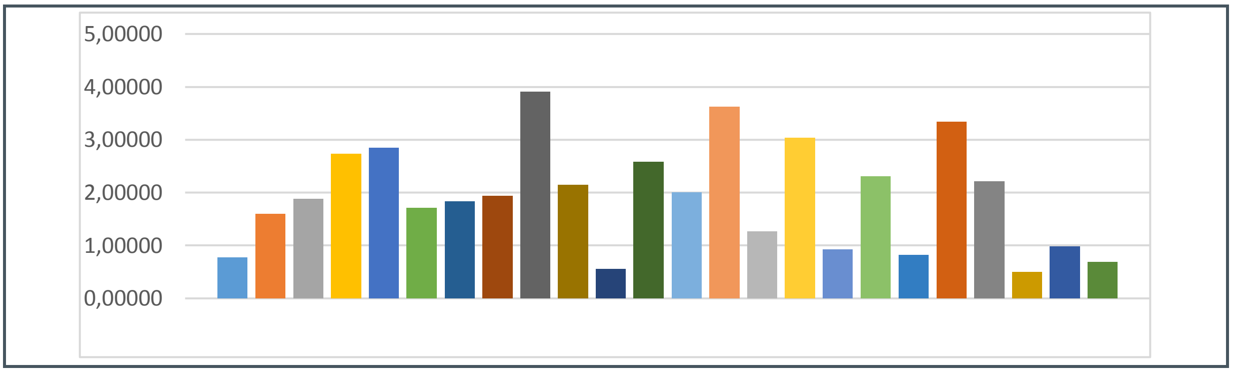
In Figure 18, all results are present in one diagram. It can be seen that each color has an own accuracy after the calibration. Therefore, always the minimum, maximum, and average (typical) deviation of the color target is interest. Accordingly, calibration can be optimized to minimize color variations or min/max/typ. for a range of colors.

Figure 17 :
Using 24 Targets[11] to Correct Sensor Results and Comparison with Reference

		1	2	3	4	5	6
		Dark Skin	**Light Skin**	**Blue Sky**	**Foliage**	**Blue Flower**	**Bluish Green**
Sensor correction	**X**	11,60	37,83	16,93	9,59	23,23	29,83
	Y	10,75	35,17	17,90	12,13	21,57	41,57
	Z	7,83	25,94	34,07	6,28	41,98	43,80
DIFF Spec/Sensor	**X**	0,3223	1,3730	1,2074	1,5138	2,4631	1,4888
	Y	0,3566	1,5647	1,3427	1,8081	2,4934	1,4311
	Z	0,3813	1,6687	1,3923	1,1745	2,9789	1,9006
Spectrometer xyz	**x**	0,3874	0,3865	0,2490	0,3416	0,2712	0,2610
	y	0,3568	0,3563	0,2641	0,4291	0,2540	0,3583
	z	0,2558	0,2573	0,4868	0,2293	0,4747	0,3808
Sensor xyz	**x**	0,3844	0,3824	0,2458	0,3424	0,2677	0,2590
	y	0,3561	0,3555	0,2598	0,4334	0,2485	0,3608
	z	0,2595	0,2621	0,4945	0,2242	0,4838	0,3802
DIFF Spec/Sensor	**Delta Y (WP)**	0,4%	1,7%	1,5%	2,0%	2,7%	1,6%
	Delta Y	**3,4%**	**4,7%**	**7,0%**	**13,0%**	**10,4%**	**3,3%**
	Delta xy	**0,00302**	**0,00419**	**0,00546**	**0,00440**	**0,00656**	**0,00326**
Spectrometer L*a*b*	**L***	38,5335	64,6518	50,9668	44,1468	56,1478	71,5550
	a*	10,6542	15,6606	-0,7757	-14,8550	12,2978	-32,0381
	b*	12,2216	17,7905	-22,1414	21,8997	-24,5383	1,2131
Sensor L*a*b'	**L***	39,1504	65,8845	49,3713	41,4250	53,5641	70,5727
	a*	10,3132	14,8517	-0,4323	-14,7805	12,7536	-33,3655
	b*	11,9129	17,1979	-23,0673	21,7538	-25,6283	1,6248
	Delta *a rg	0,3410	0,8090	0,3434	0,0745	0,4558	1,3273
	Delta *b by	0,3087	0,5925	0,9260	0,1459	1,0900	0,4117
	Diff a'b'	**0,45999**	**1,00277**	**0,98760**	**0,16379**	**1,18144**	**1,38969**
	Delta E	**0,76951**	**1,58902**	**1,87646**	**2,72672**	**2,84101**	**1,70181**
	Number of targets	24					
	Summary	Results 24 targets:			**Max**	**Min**	**Average**
				Delta Y	19,15%	0,17%	5,62%
				Delta xy	0,01412	0,00025	0,00479
				Diff a'b'	3,59906	0,08516	1,28445
				Delta E	3,90622	0,49498	1,92002

[11] Tables were interrupted, see the fully tables in the original MS Excel File

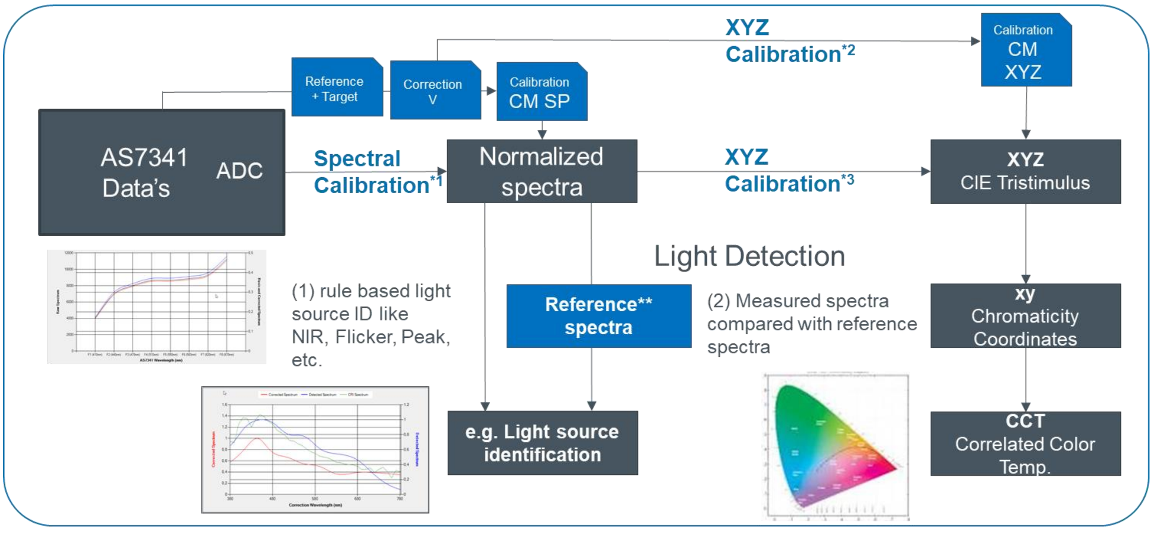
Figure 18 :
Delta E after Correction, Using Direct XYZ Device Calibration



3.5.2 Example ALS

In the second Excel sheet, all steps from ADC Sensor values to 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 AS7341 GUI. The following figure shows the used processes of the alternative methods as a block diagram.

Figure 19 :
Alternative Calibration Process for 'Light Detection'



*1 from ADC results to Reconstructed Spectrum
*2 from ADC results to XYZ
*3 from Reconstructed Spectrum to XYZ

In spectral reconstruction, the calibration matrix CM for light detection is a spectral matrix with a step size of 1nm within the wavelength 400nm to 1000nm. The calibration then also 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 spectrometer results to the calibration matrices representing device-to-type calibrations.

Since all sensors have more or less deviations from this GD, all sensors must be adapted or scaled to 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).

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 for both algorithms all steps - from spectral ADC calculated BasicCounts, corrections, calibration and XYZ calculations to get the photometric results. All formulas can be checked over the fully algorithm systematic or are helpful to benchmark own software.

Figure 20 shows the Sensor data from ADC as BasicCounts, before/after corrections and lists all correction values those can be used also direct in AS7341 EVK GUI’s ALS initialization and calibration files. For more details, see the manual for AS7341 EVK.

Figure 21 presents the process from ‘reconstructed spectrum’[12] to ‘photometric results’. Figure 22 contains the photometric result, but it is based on the direct XYZ calibration. The reason for the small differences between both photometric results are the different algorithms and calibration matrices despite of 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 up to 11] dimension. The spectral reconstruction requires a matrix of [400x8 up to 11] dimension. 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.

[12] Based on a calibration file, which is inserted in another sheet. Calibration file is based on a General Calibration, which is described in this document in chapter 3.5.

Thus, each application has to be adjusted and optimized regarding its necessary functions, accuracies, and effort in calibration.

Figure 20 :
Sensor Data plus Corrections are the Basics for Calibrations

Basics - ADC BasicCounts, Offset and Scaling, Normalization

Channel Data is data taken from the AS7341, The Corr Factor is a multiplier/scaler (whole or fractional) which is based on, and specific to, the Opto-mechanical solution for a product design - accounting for the impact of Cover Glass, Inking, and other factors on light reaching the sensor at each key Wavelength across the operational spectrum of the AS7341 (here used for formal NIR correction),

User Measured Data plus corrections

Channel Data						
AS7341 Channel	**Channel Wavelength (WV)**	**Basic Counts**	**Corr Sensor Offset**	**Corr Sensor Factor**	**Data Sensor (Corr)**	**Data Sensor (Corr/Nor)**
F1	410	0,04411	0,00197	1,02811	0,04332	0,05333
F2	440	0,11519	0,00725	1,03149	0,11134	0,13707
F3	470	0,14046	0,00319	1,03142	0,14157	0,17429
F4	510	0,14953	0,00131	1,03125	0,15285	0,18817
F5	550	0,38247	0,00147	1,03390	0,39392	0,48495
F6	583	0,41821	0,00186	1,03445	0,43069	0,53022
F7	620	0,44645	0,00176	1,03508	0,46029	0,56666
F8	670	0,11951	0,00522	1,03359	0,11813	0,14543
Clear (peak)	750	0,66134	0,00300	1,23384	0,81229	1,00000
NIR	900	0,07856	0,00100	1,26942	0,09845	1,00000

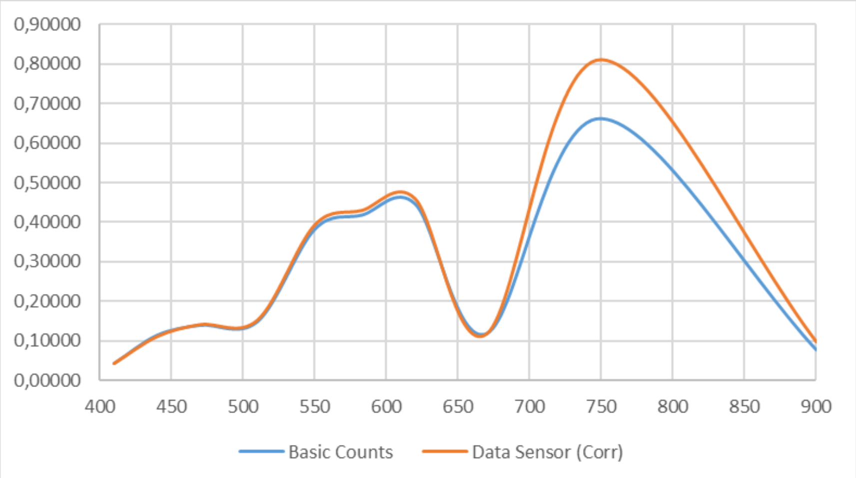


Figure 21 :
Reconstructed Spectrum[13] and Photometric Results after Spectral Reconstruction

Reconstructed Spectrum plus CIE1931 mapping plus Photometric Results

This uses the (large) **Spectral Corrrection Matrix** in the "Calibration Matrix" Sheet and **Sensor Data (Corr)** Channel Data on this page to reconstruct the full Spectral Characteristic of the Light Source from the 10 channels of AS7341 data - Ref Column E on this page

This uses the (large) **Spectral Calibration Matrix** in the "Calibration Matrix" Sheet, data from the "Standards" Sheet tables and, the calculated **Spectral Reconstruction Data** on this page to get higher-accuracy XYZ values

More Complex, Most accurate Calculation Method:
This uses the full **Spectral Reconstruction** dataset and the **Calculated XYZ** data from this page, and the (large) **Spectral Calibration Matrix** in the "Calibration Matrix" Sheet to optimize accuracy

Intermediate Calculations

Spectral Reconstruction		
WV	Reconstructed Sensor Spec	Reconstructed Sensor Spec Normalized
380	0,000818	0,041
381	0,000827	0,041
382	0,000835	0,042
383	0,000844	0,042
384	0,000852	0,042
385	0,000861	0,043
386	0,000869	0,043
387	0,000878	0,044
388	0,000887	0,044
389	0,000896	0,045
390	0,000905	0,045
391	0,000914	0,046
392	0,000924	0,046
393	0,000933	0,047

Intermediate Calculations

Calculated XYZ			
WV	X	Y	Z
380	0,000001	0,000000	0,000005
381	0,000001	0,000000	0,000006
382	0,000001	0,000000	0,000006
383	0,000002	0,000000	0,000007
384	0,000002	0,000000	0,000008
385	0,000002	0,000000	0,000009
386	0,000002	0,000000	0,000010
387	0,000003	0,000000	0,000012
388	0,000003	0,000000	0,000014
389	0,000003	0,000000	0,000016
390	0,000004	0,000000	0,000018
391	0,000004	0,000000	0,000021
392	0,000005	0,000000	0,000023
393	0,000006	0,000000	0,000026

Results based on Spectral Calibration

CIE1931 based on Golden Unit Spectral Calibration Matrix		
X	1,56753	
Y	1,52642	
Z	0,91122	
x	0,39138	
y	0,38111	
z	0,22751	
Lx	1043	lx
u'	0,23054	
v'	0,51871	
CCT	3752	K

CCT inside

[13] Tables were interrupted, see the fully tables in the original MS Excel File

Figure 22 :
Photometric Results after XYZ Calibration

Photometric Results after XYZ Calibration

Simplest Calculation Method:
This table is based on the (small) **XYZ Calibration Matrix** in the "Calibration Matrix" Sheet, data from the "Standards" Sheet tables, and **Sensor Data (Corr)** Channel Data - Ref Column E on this page

Results based on XYZ Calibration

CIE1931 based on Golden Unit XYZ Calibration Matrix

X	**1,55691**	
Y	**1,51595**	
Z	**0,88805**	
x	**0,39307**	
y	**0,38273**	
z	**0,22420**	
Lx	**1035**	**lx**
u'	**0,23099**	
v'	**0,51973**	
CCT	**3723**	K

CCT inside

4 Revision Information

Changes from previous version to current revision v1-00	Page
Initial version	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.

5 Legal Information

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