Quick Start Guide

QG000120

AquaSensor

Color and Turbidity in Liquids

AS7261 Application

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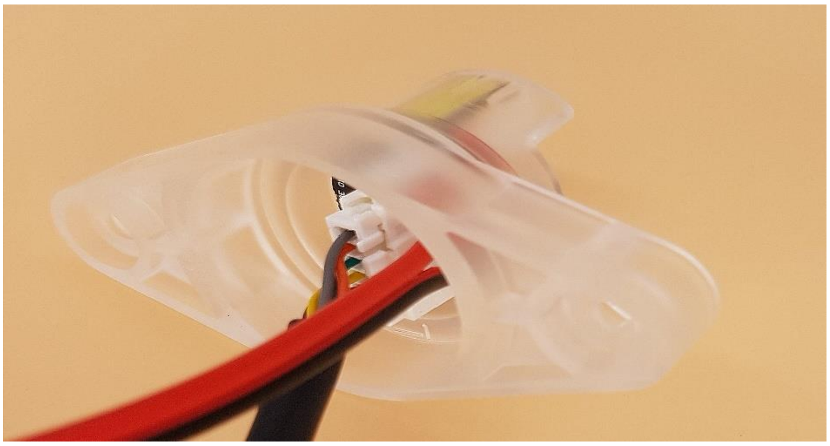
Content Guide

1 Basics of AquaSensor

The AS726x AquaSense DK is a special variant of the AS7261 Demo Kit as an application specific sensor module for liquid measurements. To the signal electronics belongs three interconnected boards. The main board includes two alternative LEDs (in standard VIS and NIR named LED 90) and connects the other two boards. The sensor board contains the AS7261 sensor chip (alternative sensor mounting is possible on request); the LED board is equipped also with two alternative LEDs (in standard VIS and NIR). The board solution as U-form is in the plastic housing, which can immerse in liquids carefully. Note that the electronic in the housing is not water proofed. Please assure that the electronics does not get in contact with water or other liquids.

More details about the sensor module you find below in the next chapters.

Figure 1:
Assembled AquaSensor



The interconnected sensor module has to connect with power supply for the alternative LEDs and with the FTDI cable and dongle between sensor and PC. Doing so, the LED driver and sensor functions is available in the standard AS7261 Demo Kit iSPI Software. For more details, see the software manual or the chapters for software in this document. The sensor module was developed to measure liquids under alternative conditions in the VIS or NIR between the optical paths ‘LED’ and ‘sensor’ trough the plastic carrier and the liquid. Note that all components of the module represent a demonstration and reference design to show typical results for such measurements. We suggest using this reference as a first step in a feasibility project to check the application and verify external effects. Note that the module has to adjust to achieve the highest accuracy and dynamic range. This optimization refers especially the optical path, the used LEDs, the sensor solution in kind of alternative spectral filters, conversion setup and corrections for floating parameters (e.g. gain error, temperature drift).

This document describes some typical aspects to show the importance.

2 Out of Box - AquaSensor

The main components in AquaSensor System pot of the Box are (see Figure 2):

1. Power supply
2. Main sensor board with embedded LED
3. Carrier case
4. FTDI connecting cable
5. USB stick with software and documents:

● AS726x reference design.pdf	Reference-design
● AS726x.Spectral.Sensing.iSPI.Application.User.Guide.3V03.pdf	User Manual
● AS726x-iSPI.Evaluation.Kit.User.Guide.2V04.pdf	User Manual
● AN_AS726x.Design.Considerations.1V01.pdf	Considerations
● AS7261_CommandSet.xls	FW command set
● AS7261_DS000493_1-00.pdf	Data sheet AS7261
● CDM21216_Setup.exe	USB Driver setup
● AS726x_Spectral_Sensing_iSPI.exe	Test software

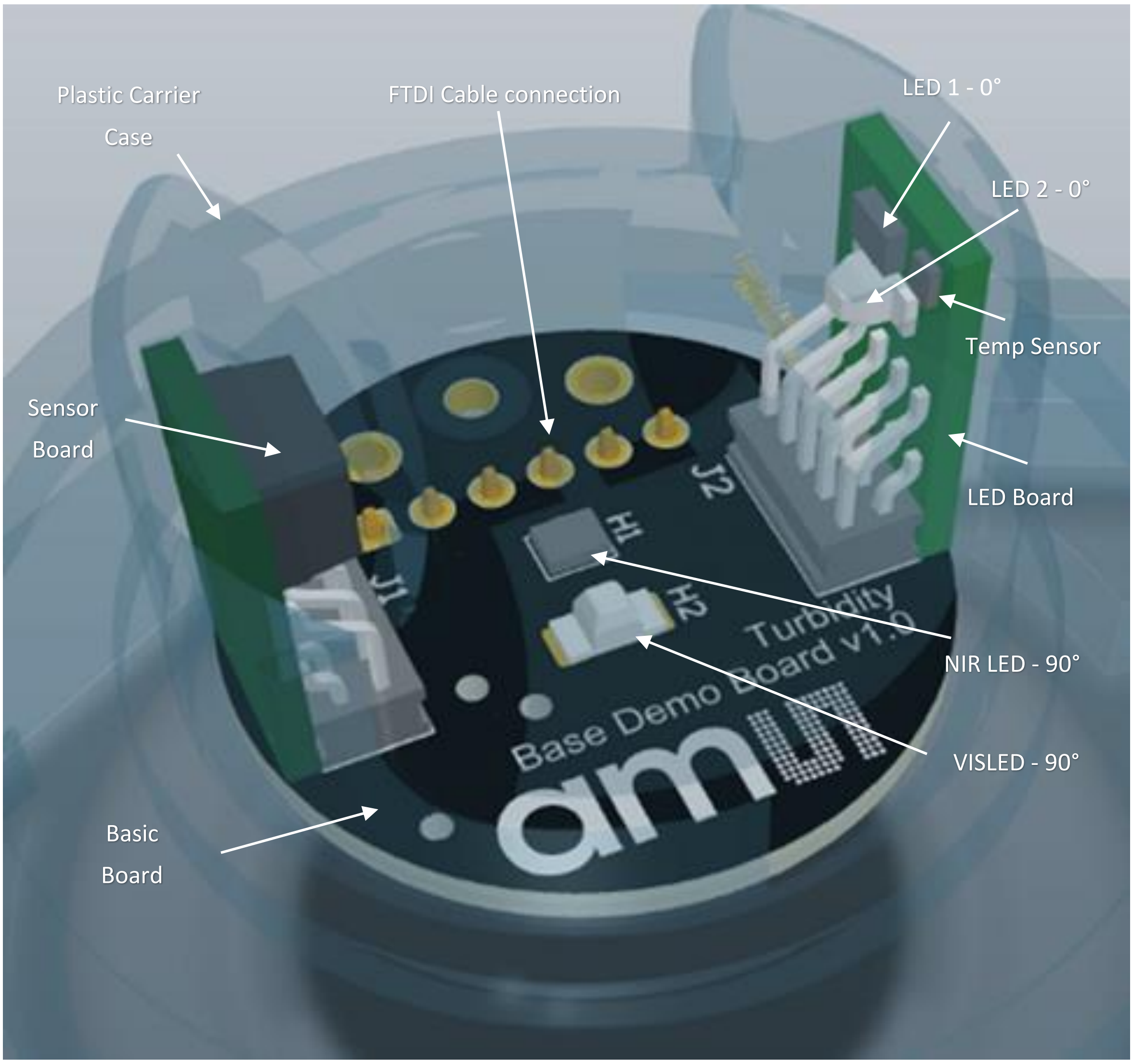
Please check if you have received all components before installation. Be careful by handling the blank electronic boards and consider all relevant ESD conditions. Electrical charges can destroy the electronics

Figure 2:
Components in AquaSensor Evaluation Kit

3 AquaSensor Test System

Figure 3 shows the main components of the AquaSensor after installing and mounting of all system components.

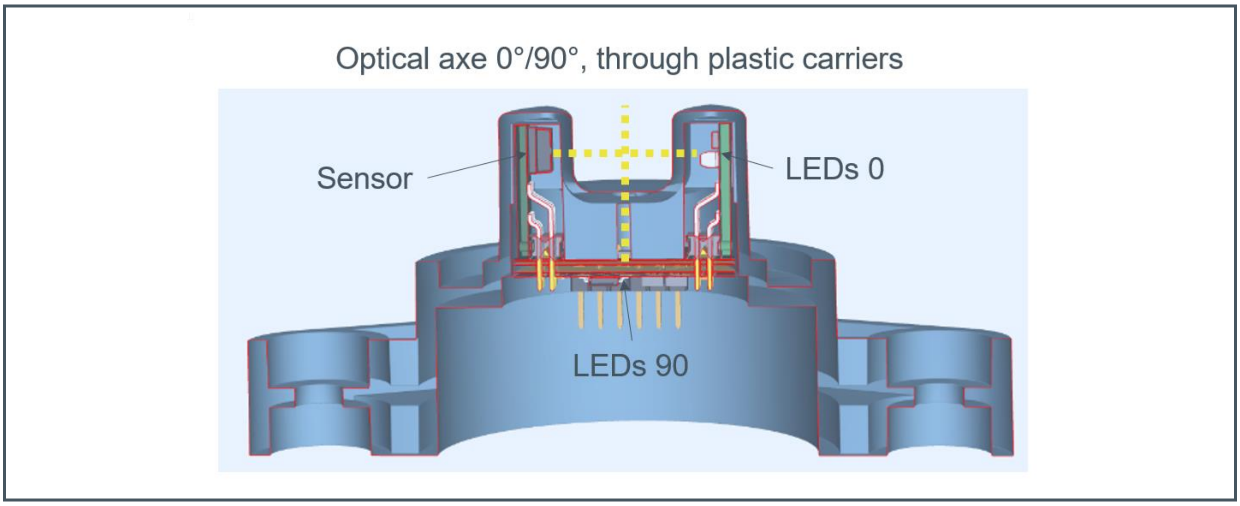
Figure 3:
Concept and Main Components in AquaSensor



Development of sensor system consist of Scotty AS7261 (VIS+ NIR) LED combinations as shown in the Figure 3. The LEDs are placed in angles of 0° and 90° to the sensor.

Figure 4 shows the optical axes 0°/90° in the standard AquaSensor module, which hast to adjust by the application/customer specific requirements (limited/fixed optical axis from LED to sensor). Note that here the optical axes represent a compromise between accuracy and flexibility as well as the selected LED/sensor combination, which must be adapted to the requirements of the application.

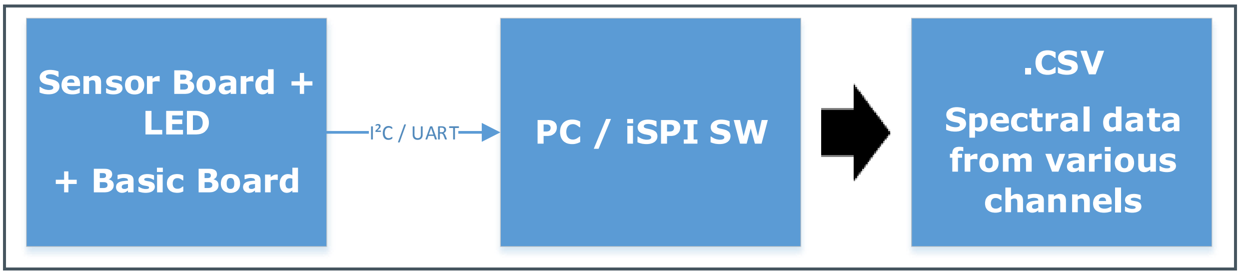
Figure 4:
Optical Axes 0° and 90°



The sensor system as three interconnected board unit or module placed in plastic carrier case to measure under application specific conditions. Note, the plastic carrier was developed and manufactured as a demo tool for various alternative applications in liquid. The housing material is a prototype material chosen as diffuser without accuracy requirements for measurements. Therefore, the material, form and all other conditions, whose affects the measurements, must be adapted.

The I²C and UART communication interface on the board makes the system compactable with PC and µC applications. A special device driver on PC is necessary as well as the iSPI test software, which was adapted. The details regarding the Sensor system in software and it functionalities can be read from the data sheet and other documentation available in the USB sticks.

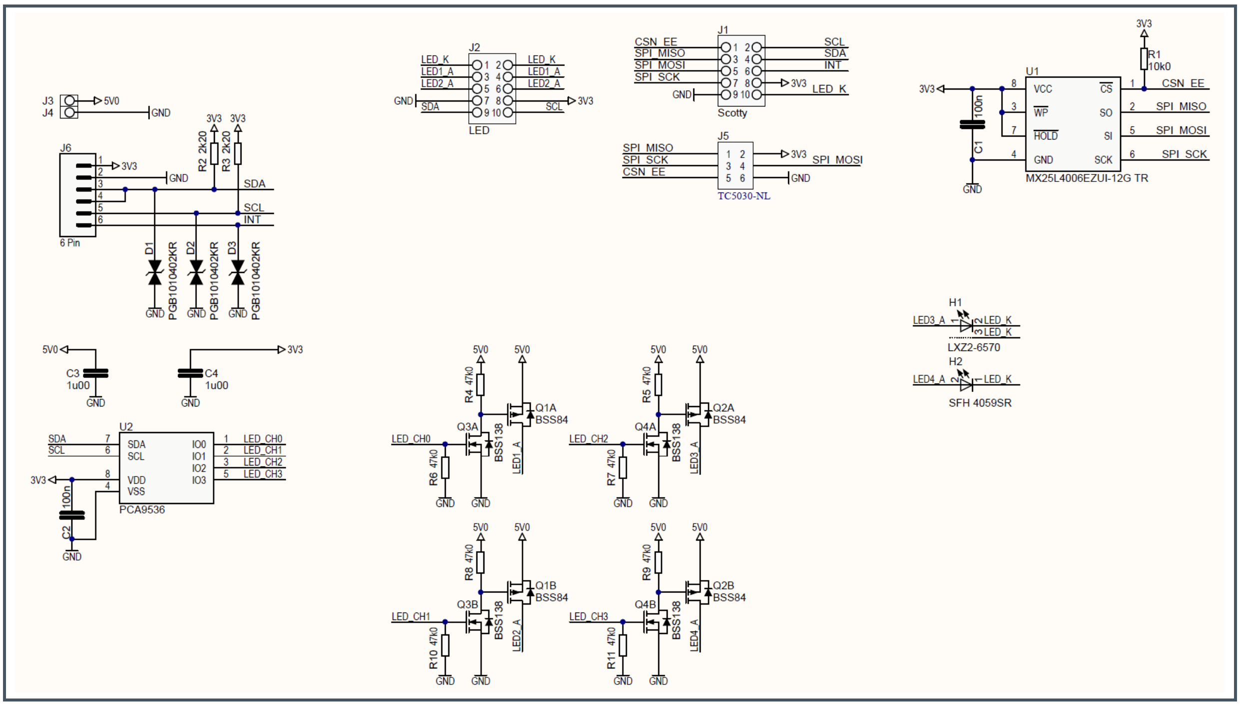
Figure 5:
Block Diagram Showing the Connection Interfaces in AquaSensor



3.1 Mainboard

The Mainboard used to connect the LED / Sensor board as well as the sensor unit in the housing. Further, it contains two alternative LEDs (named VIS/NIR 90) which useable as indirect light source.

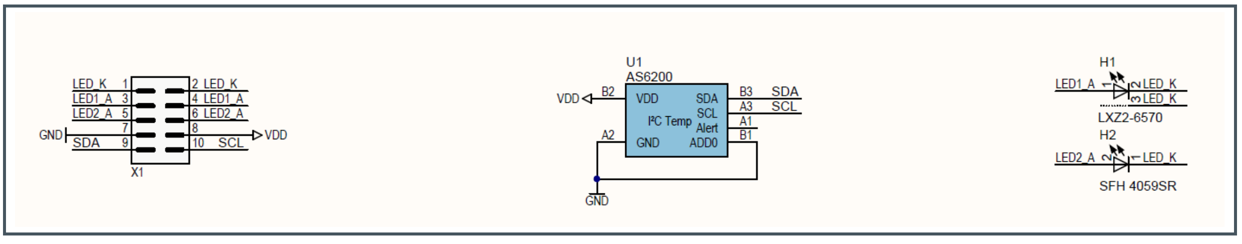
Figure 6:
Schematic AquaSensor Mainboard



3.2 LED Board

The LED board contains two alternative LEDs for the VIS and NIR range. Figure 7 shows the schematic and types of the mounted LEDs. Note, the APP team of **ams** can support you to select or change the actual used LEDs by another LED based on special requirements.

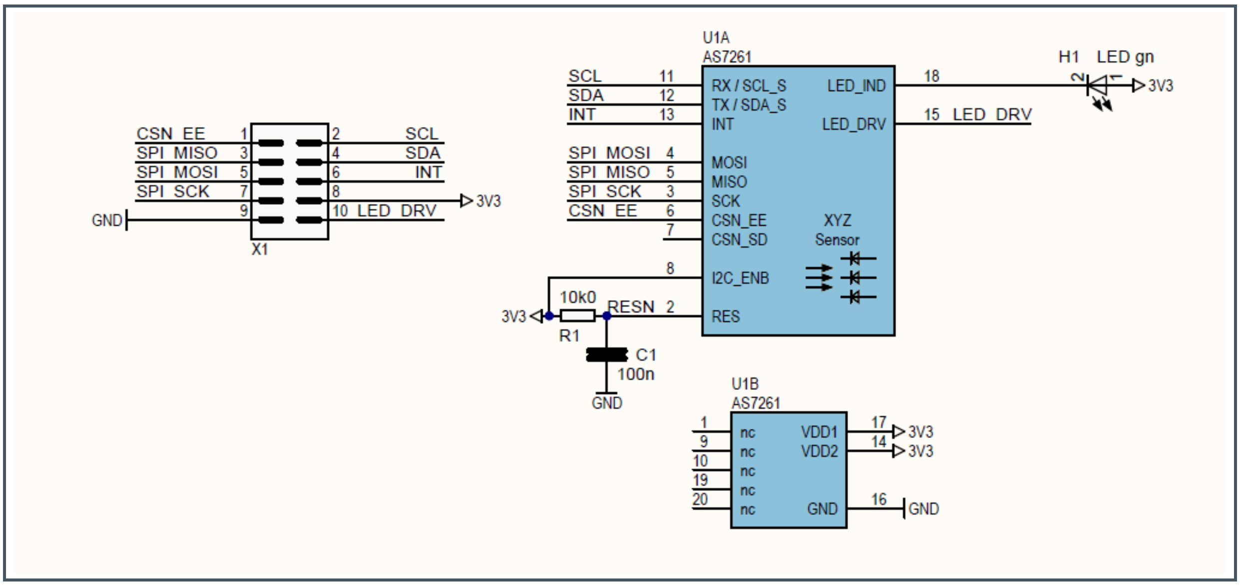
Figure 7:
Schematic AquaSensor LED Board



3.3 Sensor Board

Figure 8 shows the schematic of the sensor board. The AS7261 sensor (part of the AS726x family, AS7261 can be changed by another member of the AS726x spectral sensor family) is used as standard for the demo because the sensor combines XYZ filters (based on CIE1931 standard), a clear filter (CMOS sensitivity) and a width banded NIR channel. All integrated spectral optical filters consist of stable Nano-optic Interference filters, non-depend on temperatures and without changings over lifetime.

Figure 8:
Schematic AquaSensor Mainboard

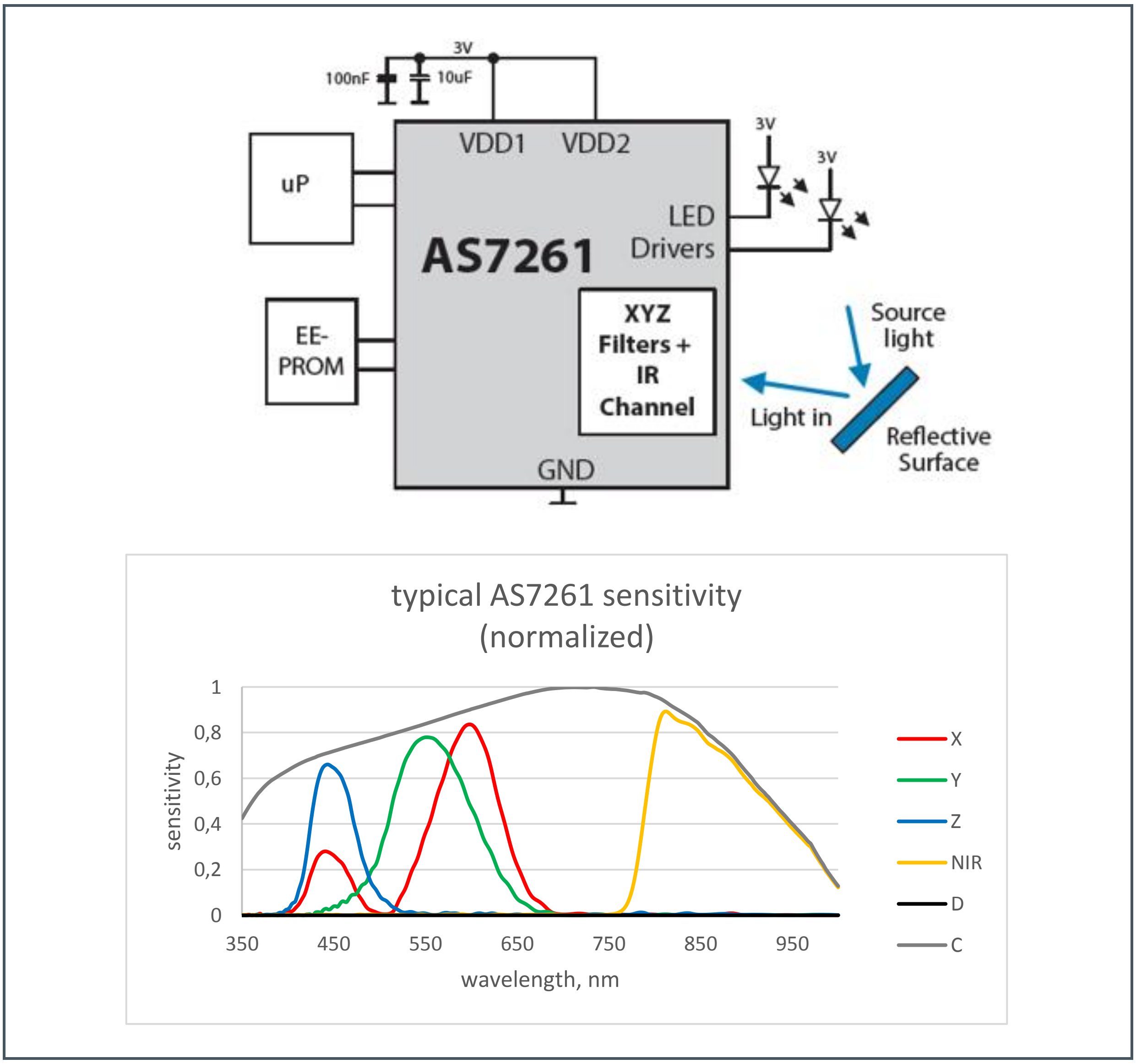


The AS726x sensor family based on a special system architecture that includes six-separated optical receiver with signal amplifier and converter, an 8051 core, various interfaces, a temperature sensor and other functions as LEDs drivers and for LED indication. The Integrated LED driver consist of two VIS LEDs and two NIR LEDs with a programmable current from 12.5 mA to 100 mA.

Depend on the special sensor type the optical receivers characterized by the type-special spectral filters and can realize so alternative applications. Listened here, the AquaSensor includes the XYZ extended with Clear and NIR sensor AS7261. This sensor can be changed very easy to another AS726x, e.g. by the 6 banded spectral sensor AS7263. Therefore, a spectral NIR measurement will be possible by (only) adaption of LED and sensor.

The below diagram shows block diagram of the AS7261 sensor and its filter diagram.

Figure 9:
Block/Filter Diagram of AS7261 Used in AquaSensor as Standard



4 How to Build and Assemble the Setup

4.1 Mechanical Setup

- Mount the Carrier Case (3) on to the Main Sensor board (2) with a screw
- Make the Connection between the power supply plug (1) and Main Sensor board (2). This supply power to LED driver on main sensor board
- Connect the FTDI Connecting Cable (4) to white connecting slot in main board (3). USB end of FTDI cable is connected to PC and is main interface to sensor and its power supply. AquaSensor and its software is designed I2C communication interface.

4.2 Software Installation

4.2.1 Items Included in the USB Memory Stick (5):

- AS72xxx FlashUpdate folder contains the details regarding various methods to flash firmware to device
- AS726x Documentation Set includes Design consideration, datasheets, application note and user guide for iSPI software
- AS726x FTDI USB-MPSSE Cable Driver contains FTDI driver file which should be installed once
- AS726x Spectral Sensing iSPI GUI includes the software and related files
- AS7261 Firmware contain the binary files for the sensor and I2C and UART command set details
- AS726x-iSPI Evaluation Kit readme.txt

4.2.2 Installation Procedures

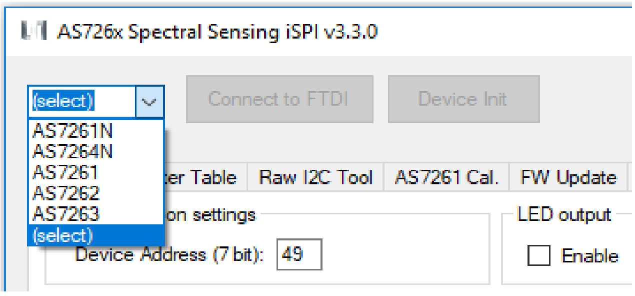
- The evaluation kit requires one time installation of FTDI CDM Driver for the USB-MPSSE cable if it is still not installed on the computer. The installation file can found in the USB Memory Stick.
- Connect the FTDI Serial Cable to AS726x AquaSensor board and USB end into PC.
- The AS726x Spectral Sensing – iSPI software does not require separate installation. Simply copy the following files to any folder on the host system and start the .exe file to start the GUI. The .NET Framework is the programming framework used to develop this application software. Thus, this software application requires 4.5 or above version of .NET Framework to be installed. It is recommend install the most up-to-date version of .NET, assuming your OS supports it.

Note: The details regarding different functionalities of GUI Software and other documentation could read from the above mention documents in USB.

5 Software Operation

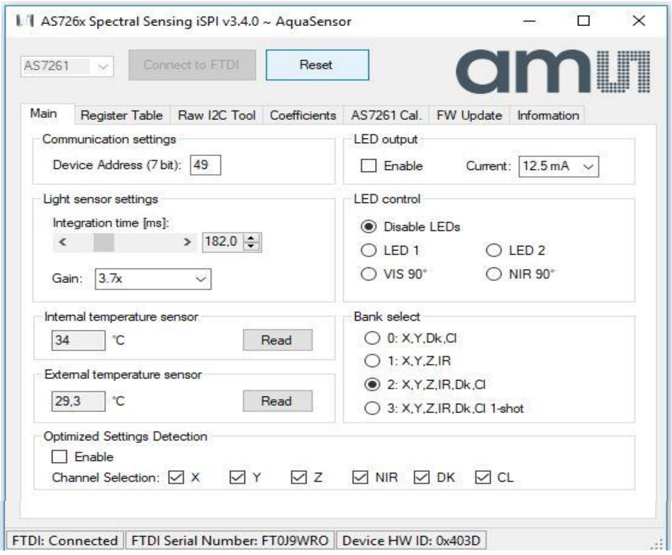
After launching the application, select the board from the top left combo box as AS7261 (as standard or select a customer specific version) as shown in Figure 10. Press the button “Connect to FTDI” and the button “Device Int” to initialize the sensor test board. An error message will printed out in case of an issue (for more details please check the software manual).

Figure 10:
Combo Box Selection for AquaSensor – AS7261



The window shown in Figure 11 and referred as Main Page will be launched when communication with the sensor has been successfully started and a hardware code named 'Device HW' is printed in the footer. Please go through the user guide and Application note in USB sticks to know the GUI software.

Figure 11:
Main Page for AquaSensor – AS7261



In the following, the specific functions of AquaSensor will described.

A hardware code is shown in the foot on the right side after selection AS7261 (or alternatives), pressing the button ‘Connection to FTDI” and ‘Initialize’. If not, then check the driver installation, USB connection and power supply. See in the manuals “AS7261 test kit’ for more details.

In general, the following steps are necessary to make stable and accurate measurements.

Steps of Feasibility

1. Select Sensor – Luminary combination
2. Stable SETUP
   ➔ e.g. fixed and shielded test system
3. Optimized parameter setup
   ➔ e.g. dynamic gain
4. Eliminate interferences
   ➔ e.g. temperatures, interfering light sources, drifts
5. Match sensor system into application
   ➔ reference and calibration

The optimized parameter setup have to select after selection the LED/Sensor combination and completion of the sensor module with running software.

To switch on a LED, it is important to check Enable from the GUI for switch-on the LED out and set LED currents in order to use the LEDs. The current can be set as 12.5mA, 25mA, 50mA, and 100mA. User can select the LEDs. Four LEDs on board can enabled separately. Two 0° LEDs and two 90° LEDs, named and defined as following:

- LED1 - mounted ion LED Board and normal White Light LED
- LED2 - mounted on LED Board and NIR LED
- VIS 90° - mounted ion LED Board and normal White Light LED
- NIR 90° - mounted ion LED Board and NIR LED

The LEDs switch on as flash (on/off) in case of LED control is not enabled but a measurement will start (Flash mode).

The parameter setup for conversion is possible by changing GAIN (amplifying) and TINT (integration time). An increasing of GAIN and TINT results higher digital counts as RAW values and sensor results; the higher the counts the better the accuracy. Note, FullScaleRange FSR needs a minimum of 182ms. On the other side, prevent saturation, which is depend on the TINT.

Raw values represents the counts from the ADC depending on the setup used (Gain, Integration time, LED-current). Basic sensor values are divided by codes, which are determined by these setup parameters. Therefore, Basic sensor counts are not depend on setup parameters or on their changing in case of using dynamic gain or Optimized Settings Detection. Note, there are affects from temperature or other interferences, which must be considered in case of dynamic gain (gain error, temperature curve, TINT linearity, synchronous operation of channels).

Basic sensor values are corrected also by multiplying raw values with temperature coefficient, which is divided by the register scaling values of Gain and Integration time.

Temperature_compensation_sheet.csv file contains the temperature coefficient values from 0°C to 100°C. While calculating the basic values the corresponding internal temperature coefficient value is take from the .csv file. User can define these values, by default it is one in .csv file. Calibrated values are calculated from the raw values based on the factory calibration. Corrected value and NTU values calculated based on raw value, the init file values and its formulas.

The init_file.txt file is present in the same folder where the .exe file and is important to have it in the folder. The initialization file is used for locating and using the defined values of certain parameter data that is used in GUI. The init_file contains the MinCounts, MaxCounts, GainScaleList, MinIntegrationTime, MaxIntegrationTime, White and black reference values for the six channels and Parameters for NTU calculation. The user can define the minimum and maximum counts for the optimization (dynamic range) of raw data in MinCounts and MaxCounts respectively. An important remark is that the scaling of gain and integration time depends on the register scaling values in firmware. The “Optimized Settings Detection” works based on these values in init_file.txt.

Save White Reference and save black reference buttons user can to save the data for Black and white reference respectively temporally. Closing the GUI, these values are erased and up on restarting the GUI, again the values saved in init file used again.

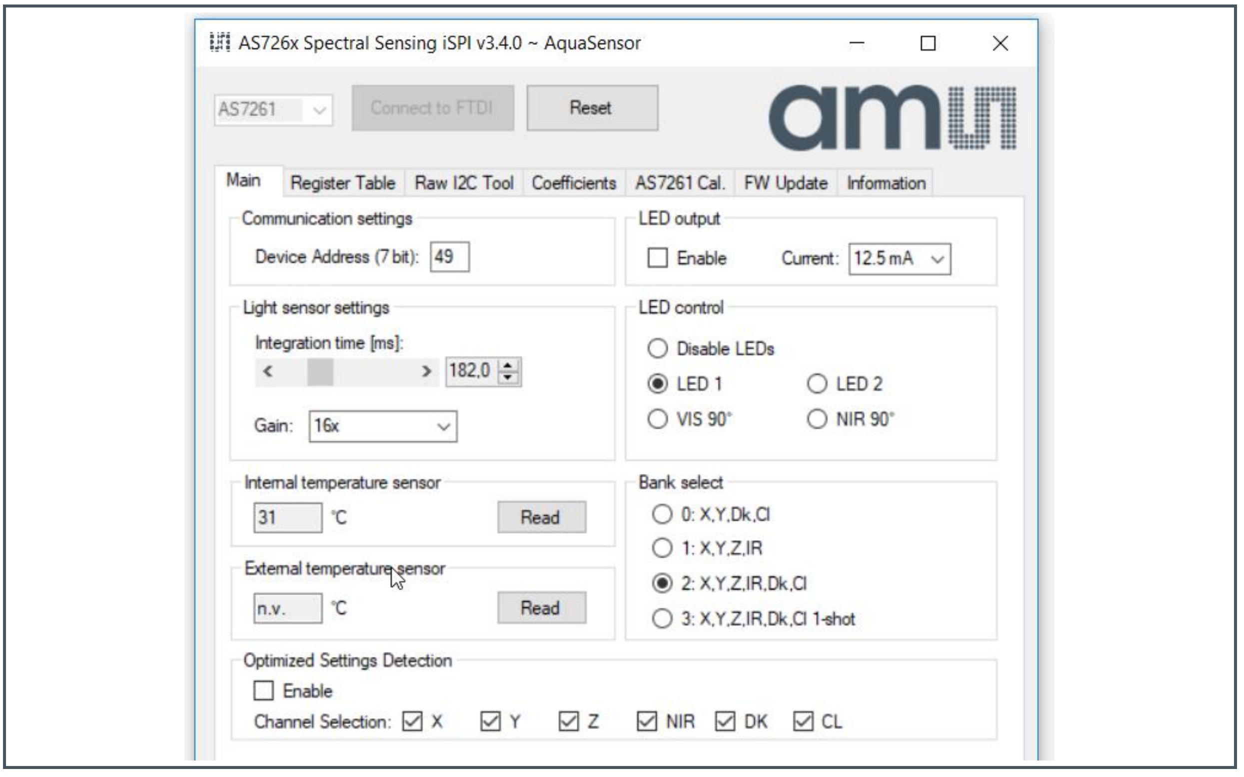
For details of these calculations or unknown procedures, please contact the **ams** customer support.

6 First Test

The following based on a connected AquaSensor and running test software with the setup shown in Figure 12.

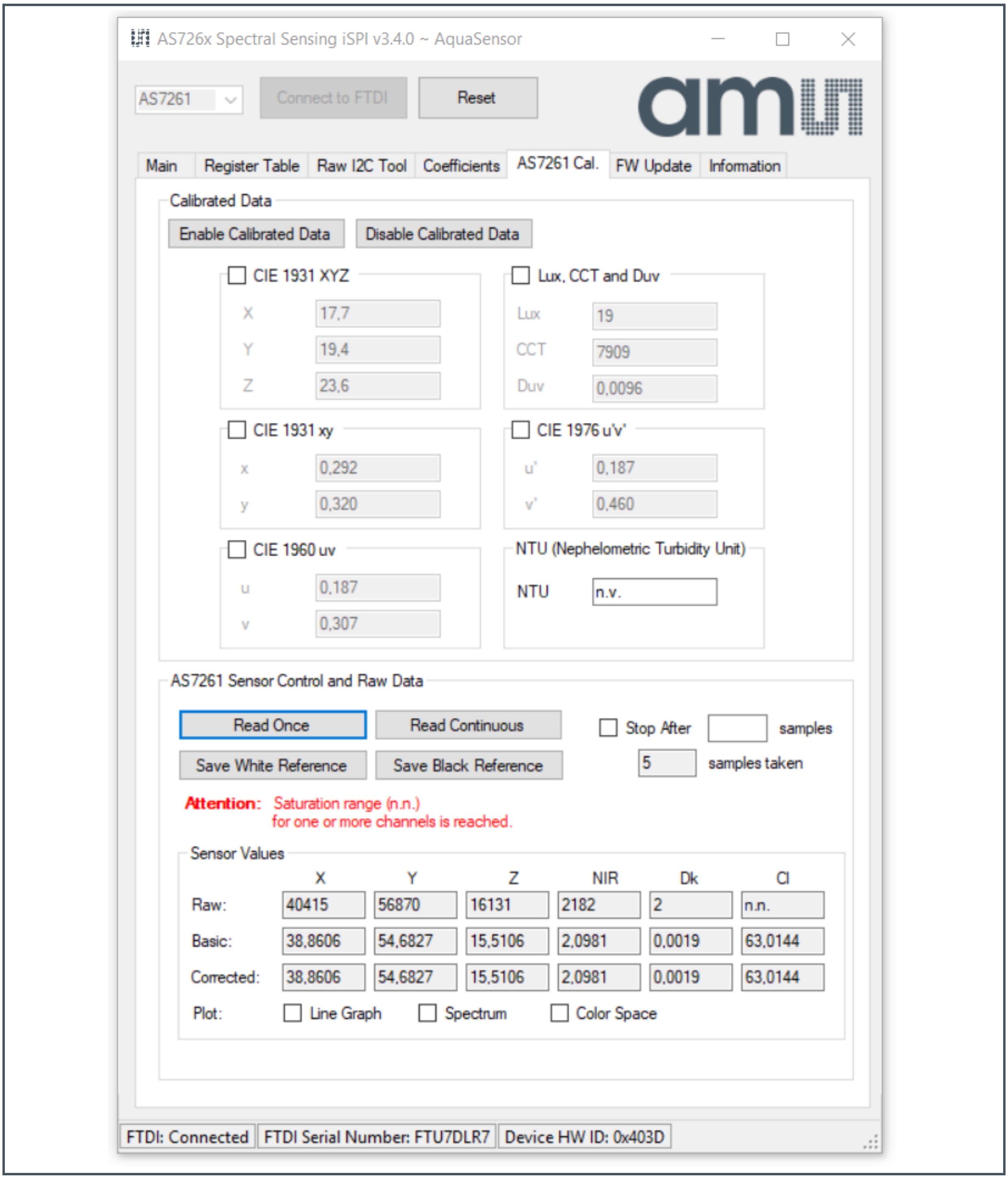
6.1 First Shoot

Figure 12:
Main Window First Step – select TINT = 182ms, Fain = 16, LED control = LED1



Go to the Windows ‘AS7261 Cal’ and press Button ‘ReadOnce’. You should get nearly the following results (see sensor results Figure 13).

Figure 13:
Read and Compare Sensor Results[1]



[1] The results in the “Calibrated Data’ are only applicable if the sensor system was calibrated based on CIE1931 conditions and the application is CIE1931 True Color Measurement. The software cannot check whether these conditions are valid. It is recommended to use this result block ‘Calibrated data” only if the conditions are valid and to use the results.

Note, the LED was 'selected' but not 'enabled'. Therefore, the LED is switched on only shortly during the measurement (Flash mode).

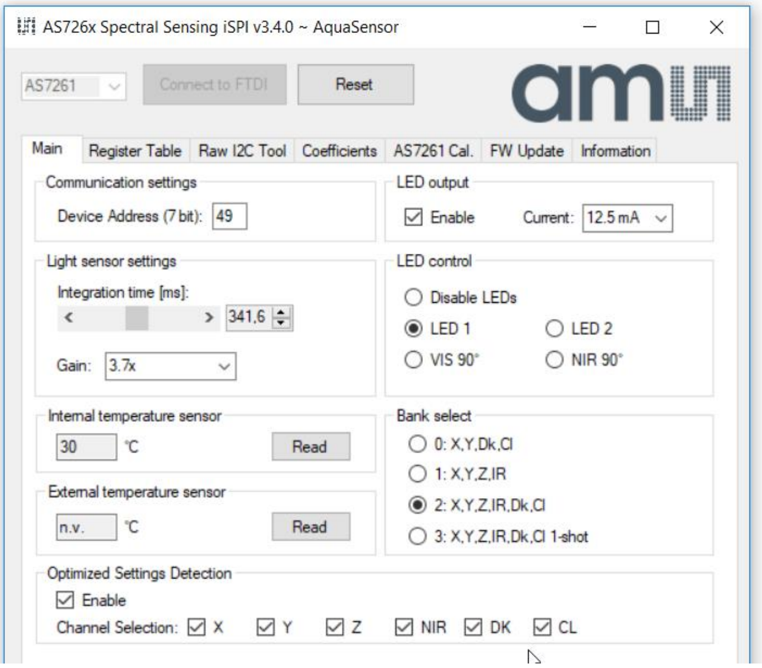
Based on the parameter setup, the raw counts for XYZ are in the upper regions of FSR, Clear and Dark[2] filters have a low response because a white LED is used and Dark should be low. The Clear channel is in saturation and out of range. Reasons for (smaller) deviations from the sensor results in the figure are standard deviations of the LEDs (bin) and sensors (non-calibrated values RAW values and different LED types), other conditions in environments (interference light) or others.

In kind of a high deviation from a standard AquaSensor in the process of a first step and the results shown here, please contact **ams** support.

6.2 Optimized

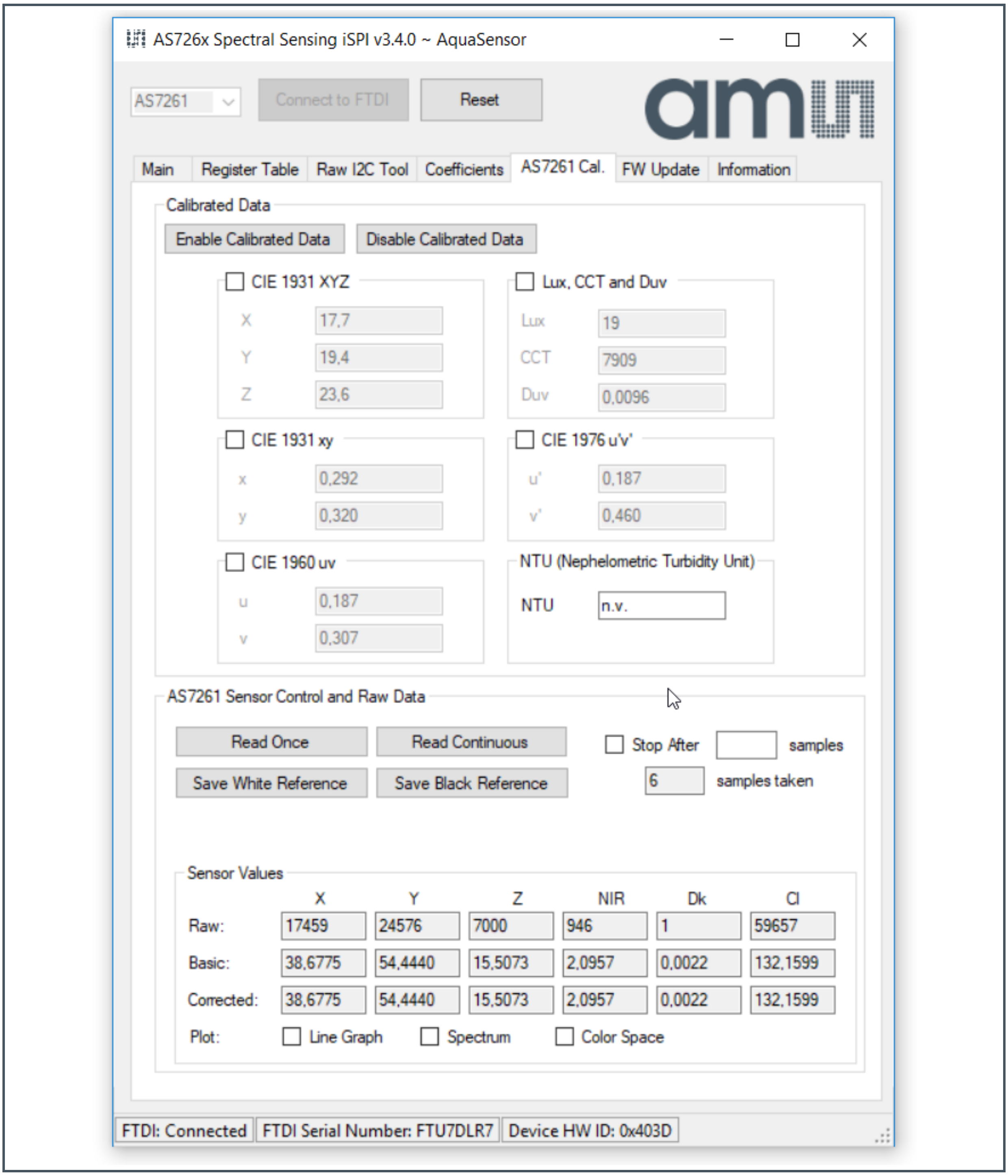
Now, go back to the Main window and switch on 'Optimized Settings detection'. Now the software enable the automatic algorithm for 'dynamic gain'. Make the new 'Read once' and compare the settings in the 'Main windows' and the sensor results in the 'AS7261 Cal'. Your results should be similar and see the reduced GAIN as the software answer for saturation in Clear, compared with the other setup.

Figure 14:
Enable Optimized Settings Detection (with the optimized setup here)



[2] Read the Sensor data sheet for details

Figure 15:
Typical Sensor Results



Measure different probes by using optical grey filters or liquids with different turbidity concentrations, e.g. from pure water to dark and/or 4000NTU. Use the dynamic gain (optimized settings detection), open a protocol file to log the data's and use the basic counts in case of dynamic gain to be not depend on the used setup. The measured sensor results can use for calibration after closing the protocol file. Make a black/white calibration to correct the existing variations of the LEDs (see chapter 7). These corrected values are the basic to match the sensor results into the application, e.g. by curve fitting to get NTU (turbidity concentrations) from the measured sensor counts. See the following example.

Figure 16:
Example 1 (measured basic counts of different sensors for alternative concentrations)

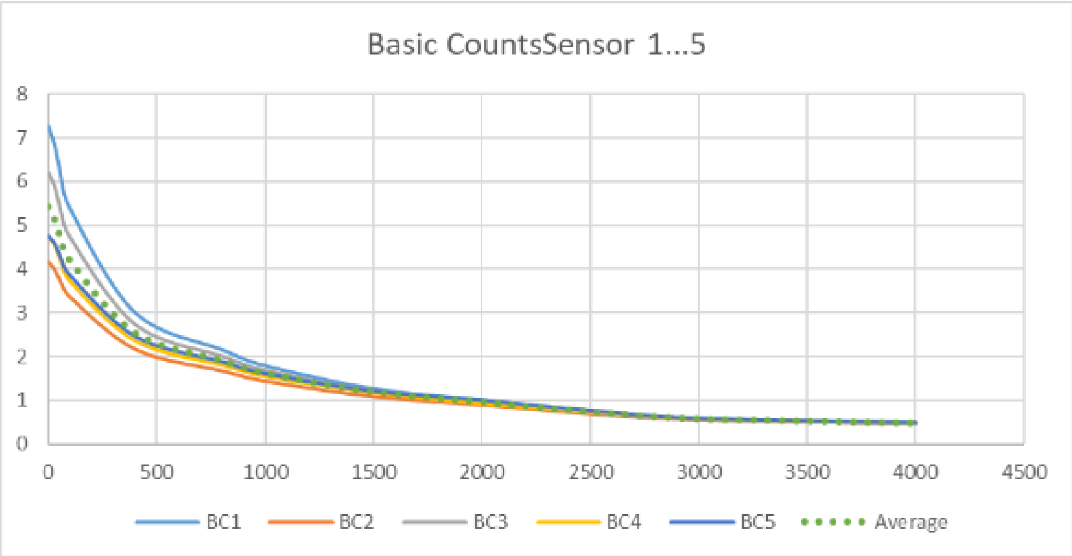
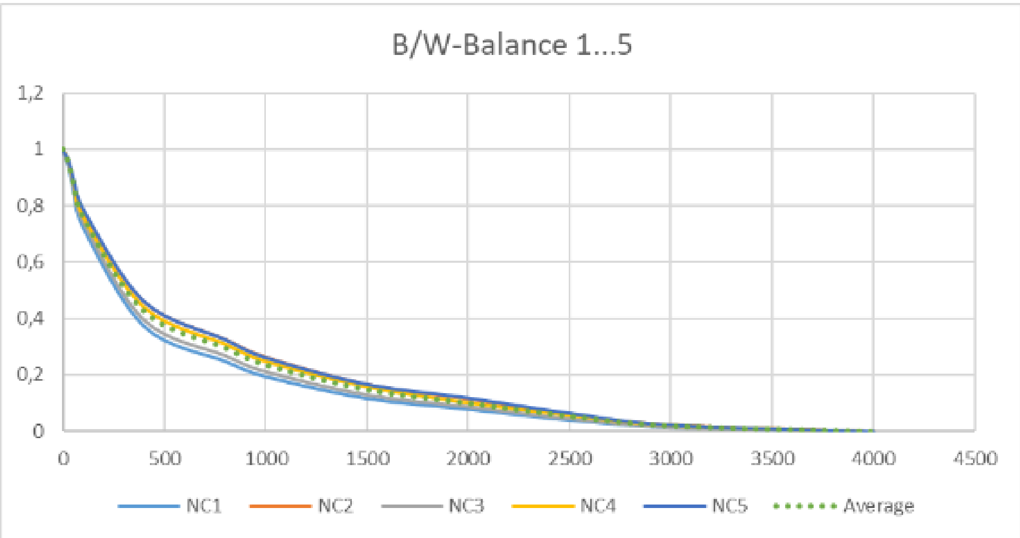


Figure 17:
Example 2 (basic counts after Black/White balance)



7 Example from Basic Counts Up to NTU

This chapter describes how to implement white-black calibration process after closing the measurement protocol to get uniformity and a result as NTU based on the measured counts. These corrected values, which are from white-black calibration, are the basic to match the sensor results e.g. NTU into the application, which named curve fitting. Turbidity will be measured from the best-fitted equation.

Here with an example, it will be explained the whole procedure about white-black calibration and Curve Fitting, based on three sensor samples, with matching the sensor results from 0 NTU (Pure Water) to 4000 NTU turbidity.

7.1 Basic Counts

After taking the measurement, put all values from all sensor into one excel file as shown in the below.

Figure 18:
#Sensor_1

NTU	X	Y	Z	NIR	DK	CL	TINT [ms]	Gain	LED Current [mA]
0	12798	22824	4899	636	1	60049	607.6	1x	12.5 mA
100	13121	22492	4650	682	1	59477	196	3.7x	12.5 mA
200	13783	22431	4501	719	1	59386	232.4	3.7x	12.5 mA
300	14369	22588	4376	763	1	59866	277.2	3.7x	12.5 mA
500	15193	22243	4180	827	1	59681	364	3.7x	12.5 mA
800	16967	22154	4130	932	1	59947	548.8	3.7x	12.5 mA
1000	17890	21994	4152	992	1	59895	700	3.7x	12.5 mA
1500	19428	21941	4405	1083	1	59768	249.2	16x	12.5 mA
2000	20695	22258	4868	1118	1	59984	347.2	16x	12.5 mA
2500	21395	22513	5319	1104	1	59785	445.2	16x	12.5 mA
3000	21624	22726	5622	1080	1	59819	515.2	16x	12.5 mA
4000	22299	23556	6357	952	1	59361	184.8	64x	12.5 mA

The following graph shows the starting point which is 0 NTU (White Balance) and ending point 4000 NTU (Black Balance) with the identical coordinates for all sensors.

Figure 19:
#Sensor_2

NTU	X	Y	Z	NIR	DK	CL	TINT [ms]	Gain	LED Current [mA]
0	11108	23304	5513	764	1	59924	624.4	1x	12.5 mA
100	11960	23262	5282	814	1	59873	204.4	3.7x	12.5 mA
200	12556	23123	5056	859	1	59891	240.8	3.7x	12.5 mA
300	13658	23306	4982	852	1	59842	285.6	3.7x	12.5 mA
500	14420	22898	4685	915	1	59530	364	3.7x	12.5 mA
800	16637	23077	4602	1021	1	59782	551.6	3.7x	12.5 mA
1000	17604	23026	4579	1131	1	59925	694.4	3.7x	12.5 mA
1500	19251	22924	4726	1182	1	59459	238	16x	12.5 mA
2000	20597	23260	5130	1229	1	59846	333.2	16x	12.5 mA
2500	21484	23646	5603	1192	1	59878	420	16x	12.5 mA
3000	21862	23907	5901	1179	1	59979	492.8	16x	12.5 mA
4000	22510	24686	6629	967	0	59568	179.2	64x	12.5 mA

Figure 20:
#Sensor_3

NTU	X	Y	Z	NIR	DK	CL	TINT [ms]	Gain	LED Current [mA]
0	19031	24357	6573	663	1	59850	635.6	1x	12.5 mA
100	18810	24290	6040	700	1	59612	204.4	3.7x	12.5 mA
200	19194	24381	5830	720	1	59801	243.6	3.7x	12.5 mA
300	19305	24249	5436	757	1	59743	285.6	3.7x	12.5 mA
500	19758	24051	5044	840	1	60020	375.2	3.7x	12.5 mA
800	20411	23482	4733	915	1	59801	560	3.7x	12.5 mA
1000	20541	23044	4577	969	1	59828	708.4	3.7x	12.5 mA
1500	21323	22654	4732	1079	1	59655	252	16x	12.5 mA
2000	21756	22487	5097	1103	1	59584	350	16x	12.5 mA
2500	22202	22740	5598	1099	1	59792	456.4	16x	12.5 mA
3000	22275	22899	5863	1081	1	59882	518	16x	12.5 mA
4000	22605	23517	6568	936	0	59111	182	64x	12.5 mA

The basic counts are calculated by following formula:

Equation 1:

$$BasicCounts = \frac{Raw\ Counts}{Gain\ *\ TINT\ *\ LED\ current}$$

Basis counts are not depending on the parameter setup and should be used as sensor results in all following calculations.

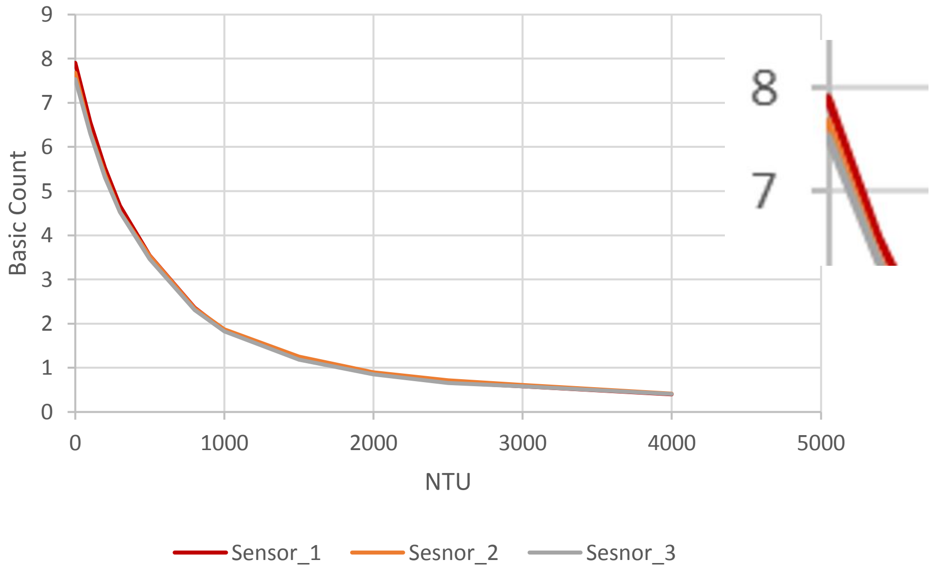
> Note, Raw counts should be corrected if the sensor system has any drift over temperature, time or by using different gains and integration times. Such issues should considered and solved by tests before calibration process starts.

As shown in the below are basic count from all three sensors based on clear channel for this example. The channel selection must be done application specific and depending on the used lamination and application to get maximum of counts and high accuracy. An optimum is depending on the used luminary, target and planed accuracy. Select the channel by a maximum of sensor filter luminary overlapping, number of affected filters and slopes and interferences. Target is to get a maximum of counts in case of minimal changing of sensor/luminary/target overlapping.

Figure 21:
Table Measured NTU and Counts of All Sensors

NTU	Sensor_1	Sensor_2	Sensor_3
0	7.90638578	7.677642537	7.53304
100	6.561169333	6.333421484	6.305813
200	5.525050007	5.377660052	5.30786
300	4.66955267	4.530395942	4.522901
500	3.545054945	3.536085536	3.458768
800	2.361791821	2.343335359	2.308919
1000	1.85003861	1.86589239	1.826056
1500	1.199197432	1.249138655	1.183631
2000	0.863824885	0.89804922	0.8512
2500	0.671439802	0.712833333	0.655039
3000	0.580541537	0.608553166	0.578012
4000	0.401521916	0.415513393	0.405982

Figure 22 :
Diagram Measured NTU and Counts



7.2 Black-White-Balance

Normalization or balancing must be done to eliminate technology and manufacturing deviations in sensing results and to get sensor uniformity. For this example, the table of measured sensor values shows different results of sensor counts between 0 NTU and 4000 NTU (see Figure 22). Sensor and LED variations, temperature drifts, ageing can be the reason for the differences in the sensor results.

For this example, the method Black-White-Balance was selected to match the sensor results into a defined dynamic range. This range will be the basic for the matching process that means to find a correlation between sensor results COUNTS and application specific units for turbidity NTU.

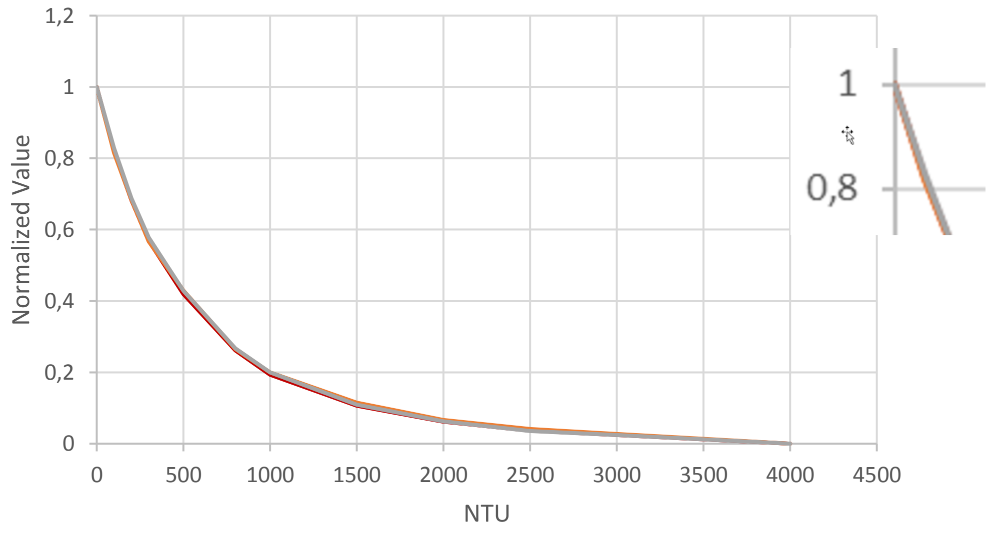
After normalization, the table will be as shown below.

Figure 23:
Sensor Results After Black-White-Balance

NTU	Sensor_1	Sensor_2	Sensor_3
0	1	1	1
100	0.820754051	0.814899869	0.827807
200	0.682694341	0.683290886	0.687784
300	0.568701955	0.566622056	0.577646
500	0.418866096	0.429704854	0.428337
800	0.261199929	0.265462363	0.267002

NTU	Sensor_1	Sensor_2	Sensor_3
1000	0.193010389	0.19971815	0.199251
1500	0.106287806	0.114790752	0.109112
2000	0.061600447	0.066445503	0.062469
2500	0.035965727	0.040941153	0.034945
3000	0.023853813	0.026581705	0.024138
4000	0	0	0

Figure 24:
Diagram Sensor Results After Black-White-Balance (3 Sensors shown here about each other)



The graph shows the starting point, which is zero NTU (White Balance), and the ending point with 4000 NTU (Black Balance), identical for all sensors but a little different between 0 and 4000 NTU.

> Note, these differences will affect the sensor system accuracy after matching and should minimized so much as possible.

The device specific Black-White-Balance should correct the sensor variations based on the mounted sensor system. Therefore, it is recommend making the Black-White-Balance during the series end test of the sensor modules. In this case, the measured values for Black and White must be stored on the sensor to readout them by Sensors Firmware if these values are necessary for the calculation of turbidity (see Chapter 7.3).

The counts and/or calculated values for the sensors are the basic for the matching and correlation counts into NTU.

7.3 Curve Fitting

Curve fitting will find out a formula as correlation counts and NTU based on the normalized values of the Black-White-Balance. MCU needs this formula with the device specific parameters to make a calculation NTU values according to sensor-normalized value. The process curve fitting is to get the best-fit line or curve for the series of data points (see Figure 24). This curve fitting will produce an equation that can be used to find the points anywhere along the curve.

The curve fitting will affected by the formula type and its parameters. For the used example, the following formula was fitted as optimal solution.

Equation 2:

$$y = an * x\text{^}n + \ldots. + a2 * x\text{^}2 + a1 * x + a0$$

```
y = calculated NTU
x = counts
a3…a0 = Spec. Sensor parameter from Golden Device, type,
         lot, or device specific
```

The type of formula describes the principal correlation between counts and NTU. The parameters determine the accuracy of the correlation. The better the formula and especially parameters map the correlation the better will be the result and sensor accuracy. Therefore, a using of sensor device specific formula and parameters consider the device specific deviations and promise the highest accuracy. On the other side, it needs the highest effort in matching and device calibration. A type or lot fitting cannot consider the exemplary deviations and deliver an averaged accuracy by a lower effort.

7.3.1 Curve Fitting for Golden Device

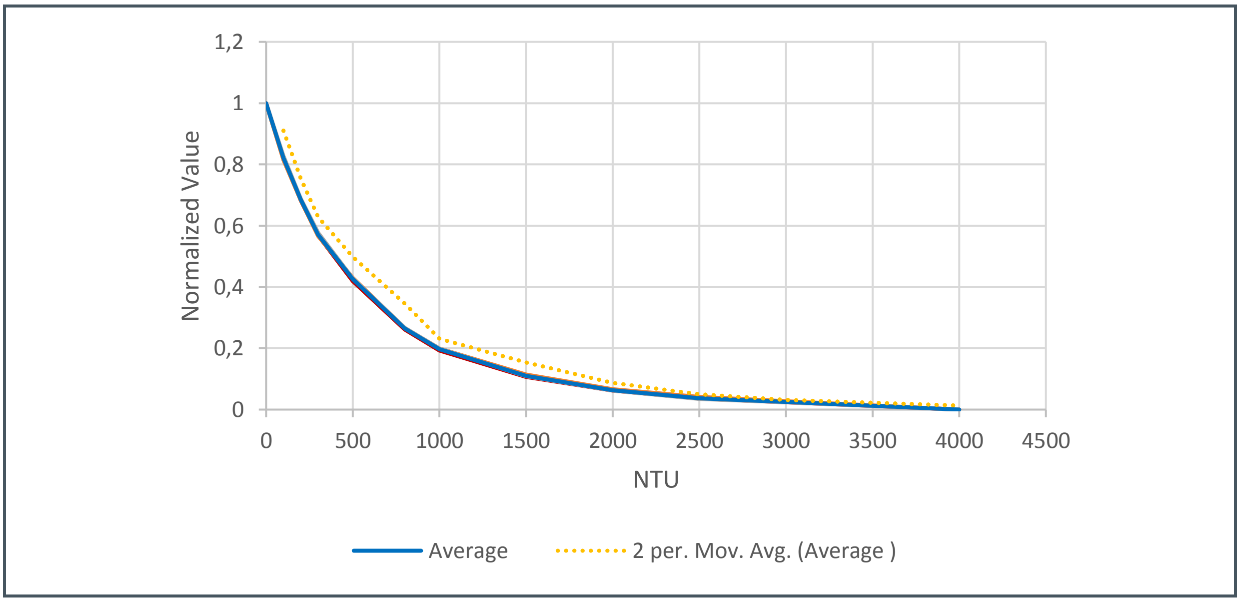
In the Golden device calibration, the balanced curves of a Golden Device (in the example, the averaged values from all sensors were used) is used to realize a correlation as formula which can be used in the sensor’s firmware.

Figure 25:
Averaging of Sensor Results

NTU	Sensor_1	Sensor_2	Sensor_3
0	1	1	1
100	0.820754051	0.814899869	0.827807
200	0.682694341	0.683290886	0.687784
300	0.568701955	0.566622056	0.577646
500	0.418866096	0.429704854	0.428337
800	0.261199929	0.265462363	0.267002
1000	0.193010389	0.19971815	0.199251
1500	0.106287806	0.114790752	0.109112

NTU	Sensor_1	Sensor_2	Sensor_3
2000	0.061600447	0.066445503	0.062469
2500	0.035965727	0.040941153	0.034945
3000	0.023853813	0.026581705	0.024138
4000	0	0	0

Figure 26 :
Averaging of Sensor Results – Diagram (3 sensors shown here about each other with Average and fitted Curve)



In the process of curve fitting,

- the inputs are the counts on the x-axe.
- the results will be the matched NTU on the y-axe.

MATLAB was used as CAD tool for the process of curve fitting (like TRENDLINE function of MS EXCEL in diagrams, see the yellow broken line ín Figure 26).

First tests show a higher accuracy in case of splitting the curve into three partitions with alternative a0…a3 parameters for the identical function of x-axe [0:500], [500-1500], [1500-4000]. These partitions result 3 alternative parameters sets for a0…a3 and must be realized in sensor's firmware as IF THEN commands.

The tests with the MatLab script result the following for the 3 sensor diagrams. As 0 NTU to 4000 NTU, there are so many points, a cubic equation is suitable for these. System will be unstable, if order of the equation will be increased.

Therefore, the equation for our example here is:

Equation 3:

$$y = a3 * x^3 + a2 * x^2 + a1 * x + a0$$

Below is the MatLab script where we used NTU and Normalization values from the example:

```
% Input data

NTU = [0 100 200 300 500 800 1000 1500 2000 2500 3000 4000];

normalized =[1  0.821153754 0.684589804 0.570990128 0.425636141 0.264554678
0.197326558 0.110063581 0.063504876 0.037284066 0.024857677 0];

%% 0 to 500NTU

x1 = normalized(1:5);

y1 = NTU(1:5);

Output(1,1:4) = polyfit(x1,y1,3);

%% 500 to 1500NTU

x2 = normalized(5:9);

y2 = NTU(5:9);

Output(2,1:4) = polyfit(x2,y2,3);

%% 1500 to 4000NTU

x3 = normalized(9:12);

y3 = NTU(9:12);

Output(3,1:4) = polyfit(x3,y3,3);
```

After execute the script, three equations have been produced as shown below.

Figure 27:
MatLab Produced Parameters

NTU	a3	a2	a1	a0
0 - 500	-1488.89	4097.258	-4318.98	1710.256

NTU	a3	a2	a1	a0
500 - 1500	-56896.6	53942.54	-18440.5	2963.21
1500 - 4000	8628314	-536391	-32227.1	4000

The following formulas can be used now to describe the correlation between x-counts and y-NTU.

```
IF x <= 0.425636 THEN y = -1488.89*x^3 + 4097.258*x^2 - 4318.98*x + 1710.256

IF x >= 0.425636 AND
   x <=0.110064 THEN y =-56896.6*x^3 + 53942.54*x^2 - 18440.5*x + 2963.21

IF x > 0.110064 THEN y = 8628314*x^3 - 536391*x^2 - 32227.1*x + 4000
```

In the sensor system and firmware (e.g. AS7261 firmware on flash), formula and parameters can be used directly.

Next step is the verification of the matching for all sensors by using the formulas of the 3 partitions.

Figure 28:
Golden Device

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.35911	0.35911
0.8182	100	103.8473	3.847333
0.681268	200	198.7379	1.26206
0.567806	300	306.3227	6.322699
0.421704	500	505.9002	5.900208
0.260834	800	836.0522	36.05216
0.194446	1000	998.7565	1.243497
0.10871	1500	1522.93	22.9303
0.062691	2000	2005.14	5.140247
0.036702	2500	2521.242	21.24199
0.024433	3000	3018.222	18.22151
0	4000	4000	0

Figure 29:
#Sensor _1

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.35911	0.35911
0.820754	100	102.3062	2.30617
0.682694	200	197.5854	2.414579

Normalized Values	NTU	NTU Check	NTU Diff
0.568702	300	305.3333	5.333262
0.418866	500	510.6223	10.62232
0.2612	800	835.1427	35.14269
0.19301	1000	1004.422	4.421568
0.106288	1500	1544.284	44.28363
0.0616	2000	2018.657	18.65721
0.035966	2500	2548.505	48.50461
0.023854	3000	3043.164	43.16442
0	4000	4000	0

Figure 30:
#Sensor _2

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.35911	0.35911
0.8149	100	105.8467	5.846743
0.683291	200	197.1047	2.895273
0.566622	300	307.6349	7.634897
0.429705	500	492.7785	7.221452
0.265462	800	824.6109	24.61085
0.199718	1000	978.6772	21.32281
0.114791	1500	1471.144	28.85574
0.066446	2000	1959.386	40.61417
0.040941	2500	2373.615	126.3847
0.026582	3000	2926.402	73.59757
0	4000	4000	0

Figure 31:
#Sensor _3

Normalized Values	NTU	NTU Check	NTU Diff
1	0	0.35911	0.35911
0.827807	100	98.07948	1.920522
0.687784	200	193.5078	6.49219
0.577646	300	295.5878	4.412185
0.428337	500	495.0012	4.998782
0.267002	800	820.8333	20.83332
0.199251	1000	980.4105	19.58945
0.109112	1500	1519.425	19.42547

Normalized Values	NTU	NTU Check	NTU Diff
0.062469	2000	2007.887	7.886994
0.034945	2500	2586.996	86.9955
0.024138	3000	3030.947	30.947
0	4000	4000	0

NTU Diff shows in all tables the difference between SHOULD and ACTUAL NTU by using the fitted curve to the Golden Device (here average of sensor 1…3).

7.3.2 Device Calibration

Device calibration considers a correlation function for each Black-White-Balanced curve. That means, more measurements over the fully dynamic range of turbidity must be done during the module end test. The results of these measurements are the calculated curve fitting with parameters from the test system, which must be stored on the sensor device. Such a process needs much more effort but guarantees highest accuracy. Below is the MatLab script.

```
% Input data

NTU = [0 100 200 300 500 800 1000 1500 2000 2500 3000 4000];

normalized_Sensor_1 =[1 0.820754051 0.682694341 0.568701955 0.418866096
0.261199929 0.193010389 0.106287806 0.061600447 0.035965727 0.023853813 0];

normalized_Sensor_2 =[1 0.814899869 0.683290886 0.566622056 0.429704854
0.265462363 0.19971815  0.114790752 0.066445503 0.040941153 0.026581705 0];

normalized_Sensor_3 =[1 0.827807341 0.687784185 0.577646372 0.428337472
0.267001743 0.199251134 0.109112184 0.062468678 0.034945319 0.024137513 0];

%% 0.2 to 500NTU

x1_Sensor_1 = normalized_Sensor_1(1:5);

y1_Sensor_1 = NTU(1:5);

Output_Sensor_1(1,1:4) = polyfit(x1_Sensor_1,y1_Sensor_1,3);

x1_Sensor_2 = normalized_Sensor_2(1:5);

y1_Sensor_2 = NTU(1:5);

Output_Sensor_2(1,1:4) = polyfit(x1_Sensor_2,y1_Sensor_2,3);

x1_Sensor_3 = normalized_Sensor_3(1:5);
```

```
y1_Sensor_3 = NTU(1:5);

Output_Sensor_3(1,1:4) = polyfit(x1_Sensor_3,y1_Sensor_3,3);

%% 500 to 1500NTU

x2_Sensor_1 = normalized_Sensor_1(5:9);

y2_Sensor_1 = NTU(5:9);

Output_Sensor_1(2,1:4) = polyfit(x2_Sensor_1,y2_Sensor_1,3);

x2_Sensor_2 = normalized_Sensor_2(5:9);

y2_Sensor_2 = NTU(5:9);

Output_Sensor_2(2,1:4) = polyfit(x2_Sensor_2,y2_Sensor_2,3);

x2_Sensor_3 = normalized_Sensor_3(5:9);

y2_Sensor_3 = NTU(5:9);

Output_Sensor_3(2,1:4) = polyfit(x2_Sensor_3,y2_Sensor_3,3);

%% 1500 to 4000NTU

x3_Sensor_1 = normalized_Sensor_1(9:12);

y3_Sensor_1 = NTU(9:12);

Output_Sensor_1(3,1:4) = polyfit(x3_Sensor_1,y3_Sensor_1,3);

x3_Sensor_2 = normalized_Sensor_2(9:12);

y3_Sensor_2 = NTU(9:12);

Output_Sensor_2(3,1:4) = polyfit(x3_Sensor_2,y3_Sensor_2,3);

x3_Sensor_3 = normalized_Sensor_3(9:12);

y3_Sensor_3 = NTU(9:12);

Output_Sensor_3(3,1:4) = polyfit(x3_Sensor_3,y3_Sensor_3,3);
```

After execute the script, parameters for three equations have been produced as shown below.

Figure 32:
Parameter for #Sensor_1

NTU	a3	a2	a1	a0
0 - 500	-1323.24	3687.404	-3982.38	1617.91
500 - 1500	-63310.7	58105.49	-19119	2965.753
1500 - 4000	9076520	-525149	-34559.8	4000

Figure 33:
Verification for #Sensor_1

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.30293	0.302933
0.820754	100	101.7227	1.722724
0.682694	200	196.7222	3.277821
0.568702	300	302.3258	2.325775
0.418866	500	499.5323	0.467745
0.2612	800	807.9283	7.928325
0.19301	1000	984.9833	15.01666
0.106288	1500	1514.045	14.04499
0.0616	2000	2000	2.59E-07
0.035966	2500	2500	9.04E-06
0.023854	3000	3000	1.45E-05
0	4000	4000	0

Figure 34:
Parameter for #Sensor_2

NTU	a3	a2	a1	a0
0 - 500	-1754.51	4749.629	-4833.98	1838.272
500 - 1500	-51711.7	50813.63	-18081.5	2989.899
1500 - 4000	4715348	-250013	-34305.9	4000

Figure 35:
Verification for #Sensor_2

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.58963	0.589628
0.820754	100	103.6669	3.666918
0.682694	200	193.0724	6.927648
0.568702	300	304.9704	4.970436
0.418866	500	498.8799	1.120078
0.2612	800	803.4024	3.402401
0.19301	1000	993.5627	6.437257
0.106288	1500	1505.655	5.654902
0.0616	2000	2000	2.1E-06
0.035966	2500	2500	3.71E-07
0.023854	3000	3000	9.58E-06
0	4000	4000	0

Figure 36:
Parameter for #Sensor_3

NTU	a3	a2	a1	a0
0 - 500	-1429.62	3945.723	-4206.06	1689.792
500 - 1500	-55820.2	52901.74	-18096.1	2931.335
1500 - 4000	13947966	-962403	-26325.6	4000

Figure 37:
Verification for #Sensor_3

Normalized Values	NTU	NTU Check	NTU Diff
1	0	-0.1625	0.162504
0.820754	100	100.8755	0.875452
0.682694	200	198.3115	1.688538
0.568702	300	301.214	1.214038
0.418866	500	499.7616	0.238447
0.2612	800	808.4852	8.485187
0.19301	1000	984.3481	15.65189
0.106288	1500	1514.134	14.13409
0.0616	2000	2000	7.52E-06
0.035966	2500	2500	1.07E-05
0.023854	3000	3000	2.05E-05
0	4000	4000	0

An insertion of these three cubic equations into the firmware which is vary device to device, will get the actual NTU value from three sensors according to their normalized values which are calculated from Basic count.

7.4 Conclusion

- ☑ To measure the turbidity, it is important to calculate Basic counts.
- ☑ To get uniformity for all sensors, Black-White-Balance is necessary.
- ☑ Golden device calibration can be used for one time calibration. In this case, average reading or one standard device has to be selected as a golden device. All other sensors result will be dependent on the Golden device.
- ☑ To get more accuracy, Device calibration is important. In this case, we need to calibrate every device separately

Headquarters
ams AG
Tobelbader Strasse 30
8141 Premstaetten
Austria, Europe
Tel: +43 (0) 3136 500 0