TAOS Inc.

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ams AG

The technical content of this TAOS application note is still valid.

Contact information:

Headquarters:
ams AG
Tobelbaderstrasse 30
8141 Unterpremstaetten, Austria
Tel: +43 (0) 3136 500 0
e-Mail: ams_sales@ams.com

Please visit our website at **www.ams.com**

INTELLIGENT OPTO SENSOR **Number 28**

DESIGNER'S NOTEBOOK

Developing a Custom Lux Equation

by Kerry Glover

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Description

TAOS digital ambient light sensors use a patented two photodiode approach allowing flexibility in adjusting the lux calculation. This "custom" lux equation can compensate for various system conditions such as dark glass or plastic in front of the sensor. This document describes how a custom lux equation can be developed.

The examples in the document will refer to the TSL2771 while the concepts apply to all of the TAOS dual photodiode devices. It is recommended that the reader become familiar with the TSL2771 data sheet and design notes DN29: Using the Lux Equations and DN26: ALS Ambient Light Sensing.

ALS Operation

A silicon photodiode is sensitive to light frequencies (wavelengths) from ultraviolet to near infrared light. Conversely the human eye is most sensitive to green light only. The goal of an ambient light sensor is to modify the silicon photodiode to "see" only the green light. In a lux meter this is typically implemented using a green filter in conjunction with an IR filter. This creates a "photopic" response which is correlated with the brightness of light seen by the human eye.

Many of our competitors' products use a similar approach of applying a green filter in combination with a low cost IR filter. While this works in an open environment, if placed behind glass or plastic that attenuates visible light but passes IR light, the IR light overwhelms the sensor and the reading becomes very inaccurate. An example of such a system would be a proximity sensor using IR light to reflect from a target. In this case, the glass is specifically designed to block visible light and pass IR light creating major lux measurement errors in a typical system.

The TAOS devices use two photodiodes; the CH0 diode is responsive to both visible and infrared light and the CH1 diode is responsive primarily to infrared light. By subtracting the CH1 diode response from the CH0 diode response (in the correct proportions) the calculated "lux" is responsive only to visible light and not the invisible IR light. Sunlight, incandescent light and especially dimmed incandescent lights all have a significant amount of undesirable IR light. With the dual sensor architecture TAOS devices can discriminate between fluorescent, sunlight or incandescent light and adjust the lux output according to the conditions. In addition, when the visible is attenuated and the IR is not, the lux equation can be changed to account for this such that the resultant lux is still accurate even in dark lighting conditions.

When to Generate a Custom Lux Equation

To generate a custom lux equation an accurate lux meter will be required. There are many factors that impact the accuracy of a lux meter and if an inaccurate meter is used, an inaccurate lux equation will be generated. One of the major differences between a lux meter and a light sensor is the lux meter uses a diffuser to average the light over a wide area.

The lux equation is intended to allow the two photodiodes to compensate for various amount of IR light and provide an accurate estimate of the visible light. The following discussion will start from the simplest system and advance to a more complex system.

The first step in this process is to verify whether a custom lux equation is needed or not. For a single light source such as sunlight or LED light, a lux equation may not be needed. In this case the IR content of the light will remain constant and there is no need for using the two different channel readings. In this case either CH0 or CH1 data can be simply scaled to create the lux reading. This is typically a rare case since in most systems other wavelengths of light are present. If a single source is not possible then a lux equation is needed.

For many systems a simple scaling of the lux equation generates adequate results. In order to determine if this is the case the system needs to be tested under fluorescent (or LED lighting) and incandescent lights. The section below on scaling will explain how to scale the lux equation.

If the accuracy using the scaling method is inadequate a new lux equation will be needed. In determining the complexity of the lux equation the number of different light sources that must be accurately measured must be understood. High accuracy can be obtained with any two light sources – one of which should contain a significant amount of IR energy and the other should contain little. If many different light sources must be taken into account, then an averaging of these light sources can be used to develop an average lux equation. In this situation, the most likely lighting condition should be weighted more heavily such as office lighting or home incandescent lighting.

With some lighting conditions multiple lux equations can be used to calculate the lux value based upon the ratio of CH1to CH0. One such condition that can greatly improve the lux accuracy is for dimmed incandescent light. If dimmed incandescent light sensing is important, a second segment of the lux equation will be required.

Data Sheet Lux Equation

The lux equation shown in the TSL2x71 data sheet has been determined to generate accurate lux values when the sensor is in an open environment. The lux equation from the data sheet is as follows:

CPL = (ATIME_ms * AGAINx) / (GA * 53)
Lux1 = (C0DATA – 2 * C1DATA) / CPL
Lux2 = (0.6 * C0DATA – C1DATA) / CPL
Lux = MAX(Lux1, Lux2, 0)

This is a two segment lux equation where the first segment (Lux1) covers fluorescent and incandescent light and the second segment (Lux2) covers dimmed incandescent light.

Scaling of the Data Sheet Lux Equation

When the TAOS light sensor is placed behind open apertures or light pipes, a custom lux equation is probably not needed. This is also the case for many dark glass/plastics applications. In all cases, the system will need to be calibrated by adding a GA factor to account for the reduction in light level. Simply use a lux meter to determine the ratio of the lux calculated by the part and the measure lux value and use that factor as the new GA. This should linearly scale the lux equation to account for the light loss.

GA = Lux Meter Reading / Lux Calculation using Data Sheet Equation

First Order Lux Equation Format and Generation

Lux equation can be stated in generic format as follows;

CPL = (ATIME_ms * AGAINx) / DGF, where DGF = (GA * DF)
DGF = (ATIME_ms * AGAINx) / CPL
Lux = (C0DATA – (CoefB * C1DATA)) / CPL
Lux = MAX(Lux, 0);

Note that DF stands for “device factor” and GA stands for “Glass Attenuation”, and DGF combines the two terms. The terms are separated when scaling the lux equation but combined when generating a new lux equation. The lux equation can be rearranged to produce:

Lux = (1 / CPL) * C0DATA – ((CoefB / CPL) * C1DATA)

Substituting:

K0 = 1 / CPL
K1 = CoefB / CPL
Lux = K0 * C0DATA – K1 * C1DATA

Now there is a simple equation with two unknowns. To solve for the two unknowns (K0 and K1) two points on the line are needed. These two points can be determined from data collected using two different light sources. One of the light sources should have a significant percentage of IR (incandescent bulbs, sunlight, etc) and the other should have little or no IR (LED’s, fluorescent). The sources are measured using the TAOS device (CH0, CH1, ATIME & AGAIN readings) and a lux meter.

The following equations can easily be formed where LM is the lux meter reading; F before a variable means Fluorescent reading; I before a variable means incandescent reading; DI before a variable means Dimmed Incandescent reading:

FLM = K0 * FC0DATA – K1 * FC1DATA; //Fluorescent Light Data
ILM = K0 * IC0DATA – K1 * IC1DATA; //Incandescent Light Data

Solving for K0 produces:

K0 = (FLM * IC1DATA - ILM * FC1DATA) / (FC0DATA * IC1DATA - IC0DATA* FC1DATA)
K1 = (K0 * IC0DATA - ILM) / IC1DATA

The next step is to convert these coefficients back to the normalized format with ATIME and AGAIN as parameters:

DGF = (ATIME_ms * AGAINx) / CPL
DGF = (ATIME_ms * AGAINx) * K0
CoefB = K1 / K0

As an example on lux equation generation, assume the following data set taken at 1x gain and 100ms integration time:

	Lux Meter	C0DATA	C1DATA
Fluorescent	273 (FLM)	625 (FC0DATA)	55 (FC1DATA)
Incandescent	112 (ILM)	1020 (IC0DATA)	399 (IC1DATA)

Solving for K0 and K1:
K0 = (273 * 399 - 112* 55) / (625 * 399- 1020 * 55) = 0.532
K1 = (K0 * 1020 – 112) / 399 = 1.08

Converting to normalized format yields:

DGF = 0.532 * 100 * 1 ≈ 53
CoefB = 1.08 / 0.532 ≈ 2

Second Order Lux Equation Format

The two segment lux equation can be stated in the following format;

CPL = (ATIME_ms * AGAINx) / (DF * GA) = (ATIME_ms * AGAINx) / (DGF)
Lux1 = C0DATA – CoefB * C1DATA / CPL
Lux2 = CoefC * C0DATA – CoefD * C1DATA / CPL
Lux = MAX(Lux1, Lux2, 0);

Simplifying the equation to determine the coefficients produces:

Lux1 = K0 * C0DATA – K1 * C1DATA
Lux2 = K2 * C0DATA – K3 * C1DATA

Solving for K2 and K3 produces:

K2 = (ILM* DIC1DATA - DILM * IC1DATA) / (IC0DATA* DIC1DATA – DIC0DATA * IC1DATA)
K3 = (K2 * DIC0DATA –D ILM) / DIC1DATA

Converting back to the standard format:

DGF = K0 * ATIME_ms * AGAINx
CoefB = K1 / K0
CoefC = K2 / K0
CoefD = K3 / K0

Dimmed incandescent can be added to form three equations to be used to solve for the four coefficients (with ILM shared between the two equations):

ILM = K2 * IC0DATA – K3 * IC1DATA; //Incandescent Light Data
DILM = K2 * DIC0DATA – K3 * DIC1DATA; //Dimmed Incandescent Light Data

As an example on lux equation generation, assume the following data set taken at 1x gain and 100ms integration time (note the incandescent data is a shared point at the end of one segment and the beginning of another):

	Lux Meter	C0DATA	C1DATA
Incandescent	112 (ILM)	1020 (IC0DATA)	399 (IC1DATA)
Dimmed	17 (DILM)	317 (DIC0DATA)	157 (DIC1DATA)

Solving for K2 and K3:

K2 = (112 * 157 – 17 * 399) / (1020 * 157 – 317 * 399) = 0.32
K3 = (0.32 * 317 – 17) / 157 = 0.538

Converting to normalized format yields:

CoefC = K2 / K0 = 0.32 / 0.532 = 0.602
CoefD = K3 /K0 = 0.528 / 0.532 = 1.01

The final lux equation for this example is:

CPL = (ATIME_ms * AGAINx) / 53.2
Lux1 = (C0DATA – 2.03 * C1DATA) / CPL
Lux2 = (0.602 * C0DATA – 1.01 * C1DATA) / CPL
Lux = MAX(Lux1, Lux2, 0)

When these equations are rounded to two digits of accuracy, they yield the data sheet lux equation.

Lux Equation Generation – EVM Software

A lux equation generator tab is available with the EVM v4.2 software to calculate new coefficients for TSL2x7x devices.

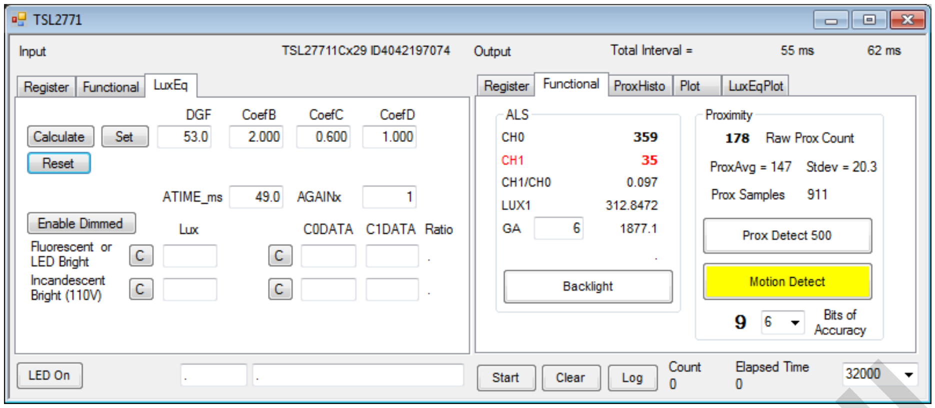

Figure 1 – Lux Equation Generation with EVM Software

For each light source the lux, C0DATA and C1DATA values must be recorded along with the integration time (ATIME) and gain setting (AGAIN). The time and gain should be the same for all data collected. The initial settings for the ATIME_ms and AGAINx are taken from the current setting on the EVM but they can be overridden. These values will change automatically based on user changes to the EVM GUI so they should be verified as correct each time a calculation is computed. However, the values are only used in the calculation and are not programmed into the device. Use the "Functional" tab or the "Register" tab to change the values programmed into the device.

Once the lux and channel data is entered, the "Calculate" button can be pressed to calculate the lux equation coefficients. If only a single fluorescent or incandescent entry is made a new DGF and GA factor will be calculated. The DGF will be updated on the "LuxEq" input screen and the GA will be updated on the "Functional" output screen.

If both fluorescent and incandescent values are entried, pressing the "Calculate" button will generate a new set of lux equation coefficients which are displayed on the "LuxEq" input tab. In addition, a new "Custom Lux" line is added to the "Functional" output tab showing the new lux equation calculations.

In the above method, a second segment equation for dimmed incandescent will be estimated. This is adequate when dimmed incandescent light is not available for lux equation generation. If dimmed incandescent is available, then the "Enable Dimmed" button can be pressed to show the dimmed coefficient entry boxes.

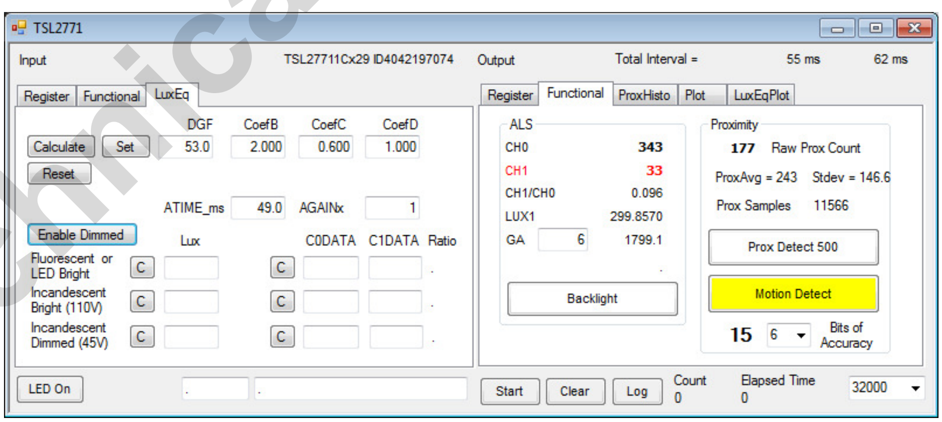

Figure 2 – Lux Equation Generation with Dimmed Incandescent

In the case where the EVM is being used to generate a custom lux equation, a “C” button has been added by each of the input data boxes. Pressing this button will automatically capture the current data from the EVM. Pressing the “C” button beside the C0DATA and C1DATA will collect both pieces of data. Pressing the “C” button by the lux will capture the lux value calculated from the EVM device as the EVM is being used as a lux meter.

The following outlines a simplified procedure for calculating the lux equation using the estimation method for dimmed incandescent and using the EVM as a lux meter for dark glass.

1. Start the EVM software
2. Change the ATIME_ms and AGAINx on the Functional (input side) tab to the target value (this may be iterative depending upon the darkness of the glass)
3. Click the LuxEq tab
4. Place the EVM below a fluorescent/LED light without the dark glass
5. Click the “C” button next to the “Fluorescent or LED Bright” and next to the Lux entry
6. Place the dark glass over the EVM (without moving the EVM)
7. Click the “C” button on the same line next to the C0DATA entry
   (If the C1 DATA is below 100 counts, the light needs to be brighter or AGAINx increased)
8. Remove the dark glass
9. Click the “C” button next to the “Incandescent Bright (110V)” and next to the Lux entry
   (If the C1 DATA is below 100 counts, the light needs to be brighter or AGAINx increased)
10. Place the dark glass over the EVM (without moving the EVM)
11. Click the “C” button on the same line next to the C0DATA entry (The voltage needs to be the standard line voltage of ~110V or 220V depending upon location)
12. Click the “Calculate” button at the top of the screen

The DGF, CoefB, CoefC and CoefD data boxes will be filled with the calculated values and the new lux value will be displayed on the “Functional” output screen. If using a CFL, make sure the bulb is warmed and the reading stable before taking a measurement.

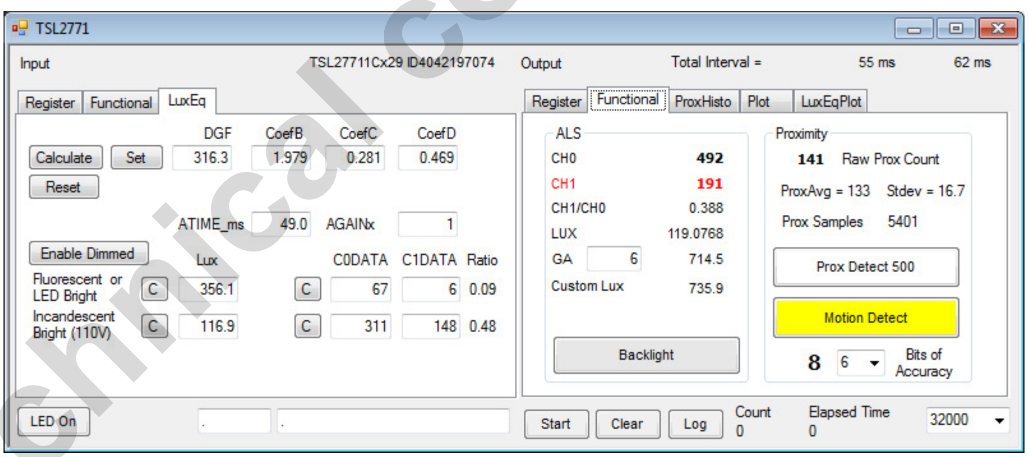

Figure 3 – Lux Equation Generation Example

There are a couple of observations that can be made to ensure the lux equation calculated is valid. CoefC should always be less than 1. The ratio for the fluorescent light should be less than 0.2. The ratio for the incandescent light should be greater than 0.3.

Lux Equation Plot

As a validation of a correct lux equation and further system analysis, a lux equation plot has been added. This plot shows the original two segment lux equation plot and the new lux equation plot.

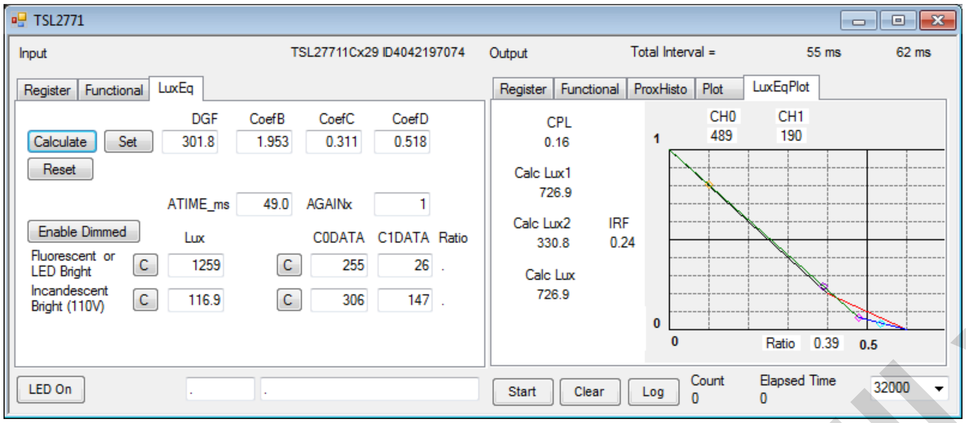

Figure 4 – Lux Equation Plot

The output screen shows the intermediate calculations for the lux equation, the CPL value and the IRF plotted against the Ratio. A spot is shown for the current calculated value as well as the captured fluorescent and incandescent points.

Lux Equation Generation – Excel Plot Method

In cases where the lux equation must be accurate for many light sources, an Excel spreadsheet plot method can be used to generate an average of the many different sources. The following is the process that can be used for this method.

The lux equation can be reformatted using the ratio of CH1/CH0 instead of CH1:

Lux = (K0 * C0DATA – K1 * C1DATA
Lux = (K0 – K1 * C1DATA/C0DATA) * C0DATA
Lux = (K0 – K1 * RATIO) * C0DATA
Lux / C0DATA = K0 – K1 * RATIO
Y = mX + B

If Lux/C0DATA is plotted against RATIO, then Excel can be used to generate a lux equation. The following is a plot from Excel using the “add Trendline” feature for that data set shown above in the lux equation generator example;

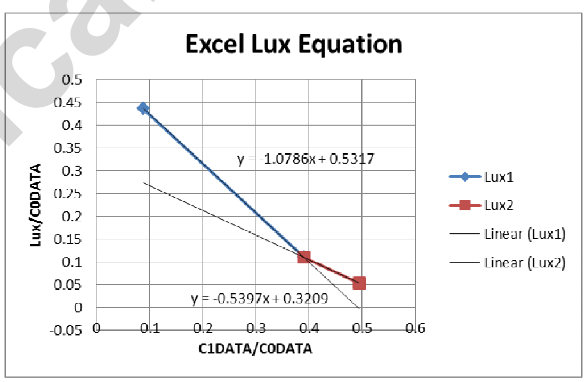

Figure 5 – Excel Lux Equation using Three Points

The first equation is y = 0.53 – 1.08x give K0 = 0.53 and K1 = 1.08, the same as calculated above. The second equation is y = 0.32 – 0.54x give K2 = 0.32 and K3 = 0.54 again the same the calculations above.

The benefit of using Excel is that many data points can be used to generate the trend-lines giving a more accurate result. By multiplying the Lux /C0DATA by the integration time and gain, the trend-line will directly read the equation time the DGF:

Lux = DGF * (C0DATA – CoefB * C1DATA) / (ATIME_ms * AGAINx)
Lux * ATIME_ms * AGAINx = DGF * (1 – CoefB * RATIO) * C0DATA
Lux * ATIME_ms * AGAINx / C0DATA = DGF * (1 - CoefB * RATIO)

The following shows such a plot with many light sources:

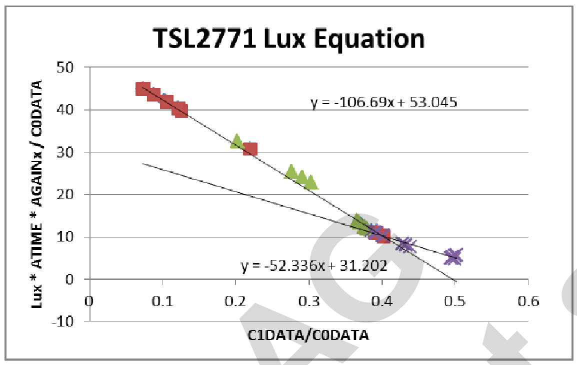

Figure 6 – Excel Lux Equation using Multiple Points

Dividing all values by 53 gives the normalized lux equation in the TSL2771 data sheet:

CPL = (ATIME_ms * AGAINx) / (GA * 53)
Lux1 = (C0DATA – 2 * C1DATA) / CPL
Lux2 = (0.6 * C0DATA – C1DATA) / CPL
Lux = MAX(Lux1, Lux2, 0)

Since the two equations are concave, the maximum of the two values can be used. An alternative is to calculate the intersection point and use the ratio of C1DATA/C0DATA to determine which equation to utilize.

Higher Order Lux Equation

Higher order lux equations are used in situation where the light source has a clear differentiated ratio and the lines can be adjusted to go through the various points. For example, the TSL2581 has several curves. These curves are a better to match Halogen light and have four segments to better approximate the dimmed incandescent conditions.

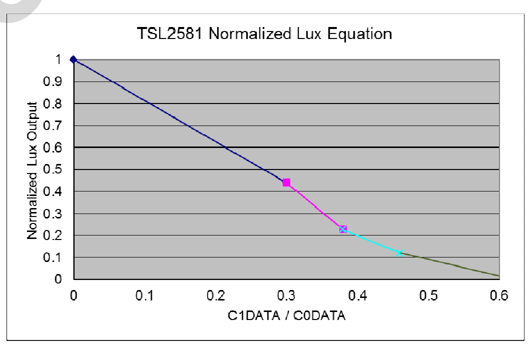

Figure 7 – TSL2581 Lux Equation using Four Segments