

General Description

The epc600/epc610 chips are time-of-flight (TOF) sensors. As every real component, these sensors have also deviations between theory and reality due to different influences e.g. imperfectness of design models or manufacturing processes, ambient influences, non perfect environments of embedding (LED, HW design), etc.

Depending on the requirements of the particular application, these effects can be handled by appropriate calibration and compensation. This document shall serve as an example how such calibration and compensation can be realized. The proposed approach is one possible method. The extend and complexity of such methods is purely determined by the respective application.

Features

- Example of an easy-to-use measurement algorithm
- Demonstration example how with three integration time values and the useful pixel dynamic range an overall dynamic range of approx. 70dB with 230 frames per second can be achieved
- Example of a temperature compensation
- Example of a background light compensation
- Example of temperature calibration procedure
- Example of a background light calibration

Applications

- TOF measurements in environments with changing temperature or background-light conditions.

1. Introduction

The epc600/epc610 chip measures distance based on the time-of-flight (TOF) principle. The basic principle is that an LED emits light to the scenery. If there is an object in the scenery that reflects light back to the epc600/epc610, the elapsed time of the light traveling from the LED to the scenery and back to the epc600/epc610 chip represents the distance to the object as follows:

$$d = \frac{t}{2} \cdot c$$

whereas:

- d distance in m
- t elapsed time in s
- c speed of light = 300,000,000 m/s

As an example, if we measure a time-of-flight of 4ns, the distance from the sensor to the object is

$$d = \frac{4 \cdot 10^{-9} \text{ s}}{2} \cdot 300 \cdot 10^6 \text{ m/s} = 0.6 \text{ m}$$

As a conclusion, the distance measurement accuracy depends on the time measurement accuracy only. However, the epc600/epc610 chip utilizes not time measurement but phase shift measurement principle. The basic concept of using the speed of light is the same in both concepts. So, the above formula is also valid for the distance measurement by the phase shift measurement principle. By using this principle, the measurement accuracy depends not only on an accurate time measurement but also on how accurate the phase shift can be acquired. By doing so, the following effects have an impact on the measurement accuracy:

No.	Effect principle	Effect on measurement accuracy	Overall impact of the measurement		Solution to increase measurement accuracy
1	System clock	linear with the clock frequency variation	very low	approx. 1mm @ 1m with a 100ppm crystal	Use an accurate crystal for the system clock
2	Temperature	second order polynomial	medium	approx. 13mm/K	Readout the chip temperature and use a compensation algorithm
3	Ambient light	linear fit (two regions)	high	up to 500mm between 0 Lux and 80 kLux	Readout the ambient light level (BG light) and use a compensation algorithm
4	Object reflectivity	higher order polynomial	medium	100mm between the lowest and highest useful signal in the pixel	Readout the amplitude and use a compensation algorithm
5	Amplitude	Distance noise	low	e.g. for epc600 and 1σ standard deviation: approx. 2.5mm in the useful amplitude range and approx. 12mm in the extended amplitude range	Averaging (take multiple measurements and take the arithmetic average)

Table 1: Effects on the measurement accuracy

This document describes how to compensate the raw data provided by the epc600 chip in order to achieve a fairly accurate distance information.

2. Goal definition

As stated in the introduction, it is the application which determines the requirements for the algorithm. In our case, we chose an application which requires continuous distance measurement with the following key requirements:

- The sensor system shall cover a dynamic range of about 70dB
- The sensor system shall operate in a time-deterministic mode with a frame rate of less than 5ms (200Hz)
- The sensor is expected to operate in conditions with strong ambient light up to 80kLux. Appropriate calibration and compensation shall therefore be deployed.
- The sensor shall be compensated for temperature induced distance drifts

3. Dynamic range considerations

3.1. Signal strength variation

By using optical principles to detect or measure objects, one has to deal with very high variation of the optical signal in the receiver. If the measurement range varies by a factor of 10, the signal strength in the receiver varies by a factor of 100 due to the following law, provided that the object size is bigger than the measurement spot on the object:

$$s = \frac{1}{d^2} \cdot k$$

whereas:

s signal strength in the receiver
d object distance
k system constant

As an example, in a typical application of the epc600/epc610 chip, the measurement range shall be between 4cm and 4m. The range variation is 1:100 and therefore, the signal strength variation will be 1:10'000. In reality, this may be less due to the lens and LED layout. Assuming that the RX lens and the LED's are spatially separated (non-coaxial design), there will be a drop in intensity at close range. The LED spot on the target and the spot mapped by the RX lens simply do not overlap anymore fully at close ranges, hence reducing the amount of light coming back to the chip. This reduces the maximal signal strength variation. A value of 1:1'000 is a valid assumption (60dB).

However, an object to be detected can also be either bright white on one hand and black on the other hand. That means that the signal strength in the receiver will also vary by the object reflectivity. Typically, a bright white has approx. 100% reflection (also called remission) whereas black may have 10% or even less.

This effect adds another 1:10 variation to the above mentioned 1:1'000 variation by the distance, because the black object can be at maximum distance and the white object is at the location with the highest system sensitivity. As a result, the total variation a distance measurement system has to deal with a signal strength variation of up to 1:10'000 or maybe even more (80dB). This is depending on the application.

3.2. System dynamic range

The signal strength in the pixel can vary from no light received (noise floor) to overexposed (saturated). No light received means just dark current is generated in the pixel (noise floor). If the incoming light does not exceed the noise floor of a given magnitude, distance cannot be measured accurately. We define the following cases:

Signal amplitude in the pixel [DN]	Classification
< 25	too less signal for an accurate measurement
25 ... 100	enough signal for a useful measurement, distance noise approx. 4 times higher than the optimum
100 ... 1'200	good signal strength
> 1'200	overexposed

Table 2: Signal amplitude versus classification

whereas:

DN Digital number of the values provided by the epc600/epc610 chip, respectively the amplitude calculation.

The above table shows, that the range of 100..1'200 DN can be used without any limitation. This represents an in-pixel dynamic range of 1:12 for reliable and accurate measurements, possible with the epc600/epc610 chip. The range between 25 and 100 can also be used, but the distance noise becomes more significant (for the epc600 from approx. 3mm to 12mm a 1σ standard deviation).

Since, we have to deal with a much higher dynamic range in real applications as described in section 3.1., additional concepts have to be applied. The epc600/epc610 chip allows to control the exposure time, also called integration time. The longer the integration time, the more light is collected in the pixel. The effect of the variation of the integration time is nearly linear. Thus, if we change the integration time by a factor of 10, the signal strength in the pixel will also change by a factor of 10 (approx.). In order to achieve a high dynamic range in the application, several measurements should be taken with different integration time in short sequence.

In order to achieve a high dynamic range with a simple algorithm, we suggest to use the following integration time set: 1.6μs, 12.8μs, 204μs. With the internal 10 MHz LED modulation operating frequency, 1.6μs is the shortest possible integration time limited by the epc600/epc610 chip. On the other end of the scale is the longest integration time. The higher the integration time, the more ambient light is collected which has also an impact on the dynamic range and the measurement accuracy. It also limits the frame rate of the system. With the proposed set of the 3 integration time values, a frame cycle time of 4.34ms can be achieved for the epc600 chip.

With these three integration time values proposed and the useful pixel dynamic range, an overall dynamic range of 76dB with 230 frames per second can be achieved.

4. Measurement algorithm

4.1. General operation algorithm

Generating accurate distance measurement data, the following algorithm shall be applied. Measurement tasks are presented in blue color, the selection algorithm is marked green and the calculation algorithm done by the micro controller is marked in pink color.

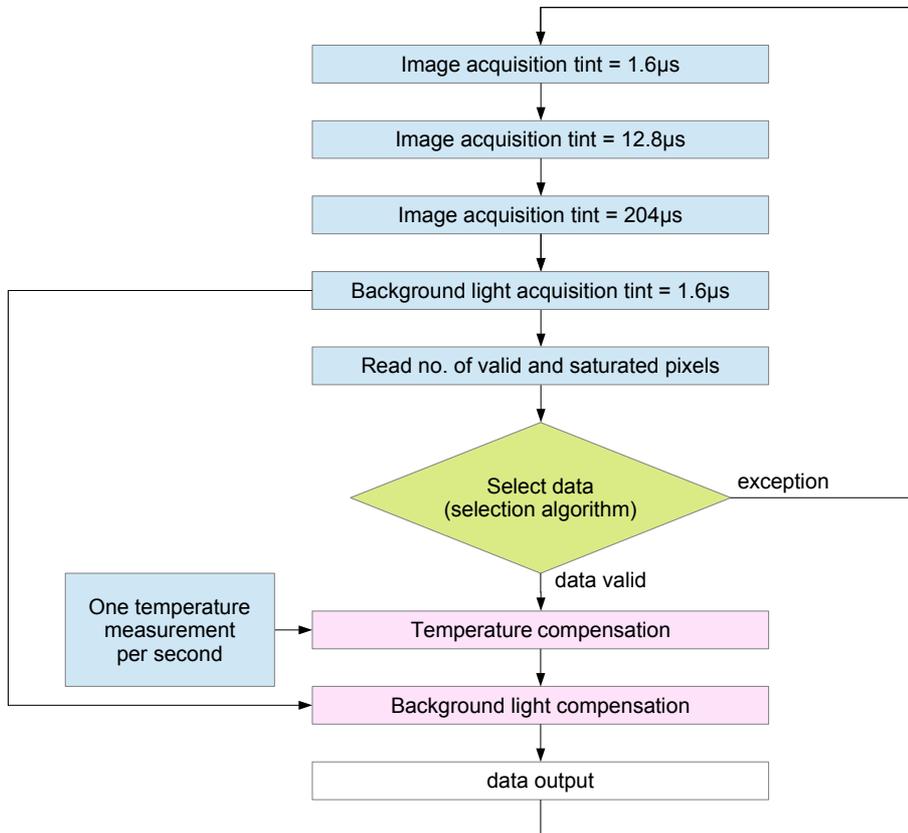


Figure 1: Distance acquisition algorithm overview

First, three image acquisitions shall be taken with three different integration times. 1.6µs, 12.8µs and 204µs. This extends the dynamic range of the pixel by 42dB and allows to measure dark object in long distance (204µs) and bright objects in close distance (1.6µs). This concept is also known as HDR or high dynamic range imaging. The measurements of the data of the three images shall be stored in the micro controller memory. This sequence is used in every measurement. The result is a time-deterministic behavior as initially specified.

In addition to that, an ambient light measurement shall be taken in order to measure the DC background light level. Since the DC background light level (also called just DC or BG) has a significant impact on the measurement accuracy, this measurement allows the compensation of this effect.

At the end, the number of valid and saturated pixels shall be read. These values are needed as an input for the selection algorithm.

Once the data is acquired, a selection algorithm checks whether the measurement data is useful or not. The measurement data is not useful, if the image is overexposed (saturated), underexposed (too less light scattered back from the object) or too less data points provide a valid signal (too few valid pixels).

If the selection algorithm found valid data, compensation of temperature, ambient light and signal amplitude effects is calculated. The result is an accurate representation of the object distance. At the end, the metric distance is calculated by the conversion of digital distance to [cm] by applying the conversion factor of 0.5 [cm/DN] to the measured and corrected distance.

The algorithms and descriptions in this paper use the following data structure & naming convention:

Input data:	Naming convention:
T (one reading per second)	T = temperature [DN]
B (for $t_{int} = 1.6\mu s$)	B = DC background light [DN]
t_{int_0} : {DCS _{0_0} , DCS _{0_1} , DCS _{0_2} , DCS _{0_3} , V ₀ , S ₀ , D ₀ }	t_{int_i} = integration time [μs]
t_{int_1} : {DCS _{1_0} , DCS _{1_1} , DCS _{1_2} , DCS _{1_3} , V ₁ , S ₁ , D ₁ }	DCS _{i_j} = differential correlation sample [DN]
t_{int_2} : {DCS _{2_0} , DCS _{2_1} , DCS _{2_2} , DCS _{2_3} , V ₂ , S ₂ , D ₂ }	V _i = number of valid pixels
	S _i = number of saturated pixels
	D _i = measured distance [DN]
	A _i = calculated amplitude [DN]

Table 3: Input data structure and naming convention

4.2. Selection algorithm

In order to identify valid data or an exception, the following selection algorithm is used.

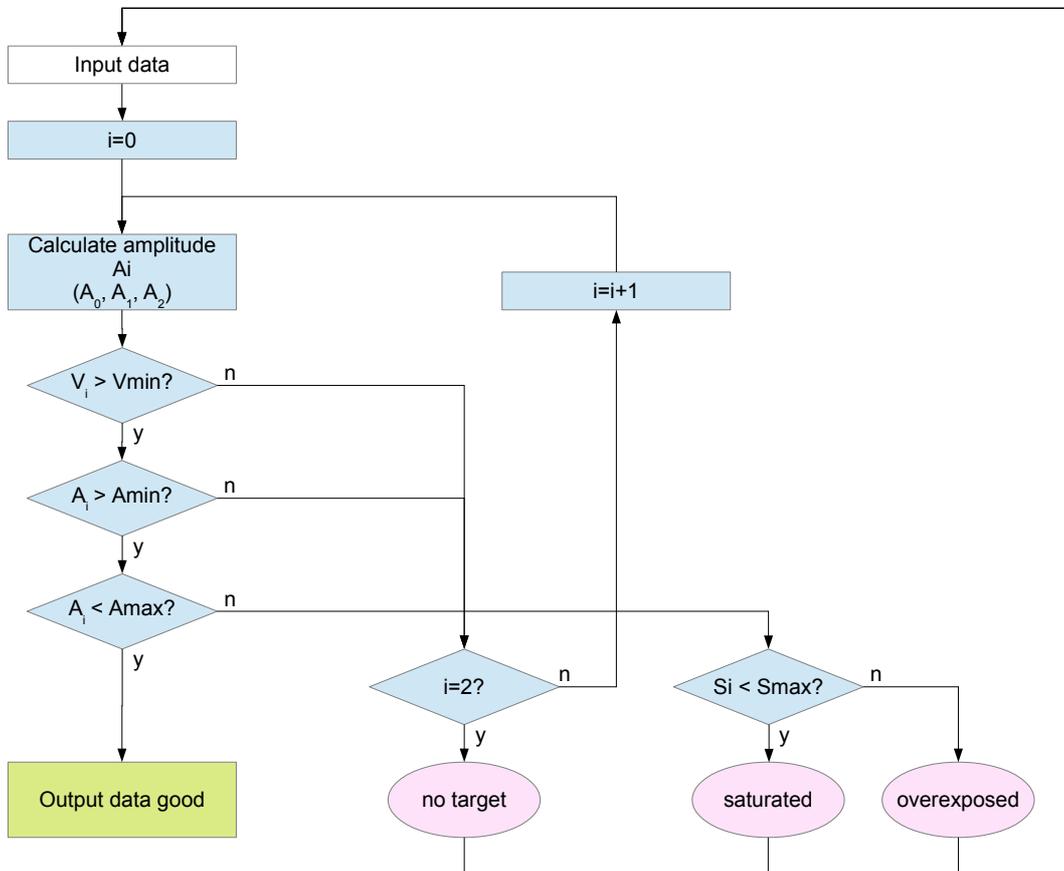


Figure 2: Selection algorithm

The selection algorithm shall use the following values (example for epc600 only):

- Vmin: 60 (minimum valid pixels)
- Smax: 5 (maximum saturated pixels)
- Amax: 1'000 (maximum amplitude)
- Amin: 100 (for minimal distance noise), 50 for increased distance noise
- i: Counter

If there is no bad data flag set (marked in pink color), useful measurement data are available as output data marked in green color. With this output data, the compensation algorithm can be applied.

4.3. Temperature compensation algorithm

The temperature compensated distance can be derived by applying the following formula:

$$D_{T_{corr}} = D_{meas} - a \cdot (T - T_0)^2 - b \cdot (T - T_0)$$

Whereas the parameters a and b are determined by the temperature calibration procedure during production of the sensor described here- under section 5.1. Temperature calibration. The temperature T_0 is the temperature readout by the chip at reference temperature.

4.4. Background light and amplitude compensation algorithm

Once the temperature compensation is done, the ambient light compensation can be applied. A simple first order model is applied with the following formula:

$$D_{B_{corr}} = D_{T_{corr}} - (m_i \cdot B + k_i)$$

Input is the temperature compensated measurement $D_{T_{corr}}$ (from 4.3. Temperature compensation algorithm) and the parameters m_i and k_i . These parameters are determined by the background light calibration procedure during production of the sensor described herein under section 5.2. Background light calibration. The background intensity B can be measured directly with the epc600/epc610 chip and must be performed with the lowest possible integration time (1.6µs). Background light level measurement has the unit of DN (refer to Figure 1). Refer to the datasheet for details on how to execute an ambient light measurement.

Note that the correlation between the measurement value B and the absolute BG level (in Lux or W/m²) is strongly depending on the optical parameters of the system and has to be established by the system integrator. Please refer to the datasheet for the known BG light sensitivity based on the irradiance on the focal plane.

In order to check if the distance data is correct, the signal-to-BG ratio (SBR) can be computed:

$$SBR = \frac{A \cdot t_{int_B}}{B \cdot t_{int_A}} \quad SBR [dB] = 20 \cdot \log_{10} \left(\frac{A \cdot t_{int_B}}{B \cdot t_{int_A}} \right)$$

with A as the computed amplitude of the distance measurement with the corresponding integration time t_{int_A} and B the background level with the corresponding integration time t_{int_B} .

In the calibration, the signal-to-BG ratio should not be smaller than -60dB in order to have a reliable signal.

5. Calibration procedure

The phase shift and the drift parameters of the epc600/epc610 chips, the illumination LEDs and the setup of the sensor vary considerably from system to system. Thus, an individual calibration has to be done per system. It consists of two steps:

1. Temperature calibration
2. Background light calibration

Note that for calibration, also the selection algorithm as described in Figure 2 shall be applied. A good calibration can only be done if the signal strength/amplitude is in the appropriate level. Exceptions marked in pink color should be discarded and only valid data should be used (green output). The calibration tasks are described in the following chapters.

5.1. Temperature calibration

An on-chip temperature sensor provides uncalibrated temperature readings. The value is in digital numbers (DN) and is used to compensate for distance drifts.

The temperature T in digital numbers (DN) obtained from the chip is nearly a linear function on the real temperature. Therefore the temperature from the chip does not need to be calibrated and is just used to compensate the distance measurement. The following formula is used to compensate the measured distance with the temperature drift:

$$D_{\text{corr}} = D_{\text{meas}} - a \cdot (T - T_0)^2 - b \cdot (T - T_0)$$

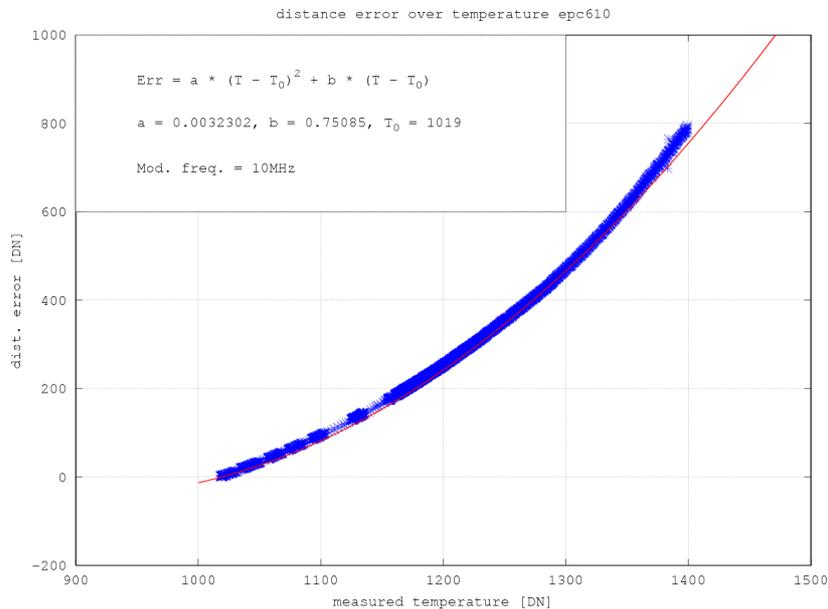


Figure 3: Distance error over temperature for the epc610 camera module V1.0 (blue marked range: approx. -10°C ... $+50^{\circ}\text{C}$)

The parameters are not only given by the chip but are greatly influenced by the characteristics of environmental components e.g. LED and the the heat sink conditions given by the mechanical design and the housing. The need to be fitted on an actual sensor sytem by using the following procedure:

1. Do the calibration measurements at a minimum (T_0), target and maximum temperature to a reference target (e.g. with 90% reflexivity) and a reference distance (e.g. 1.5m). Read for each temperature from the chip the distance value and the temperature in digital numbers (DN).
2. Calculate the distance error (E_T) for the target and maximum temperature compared to the value measured at the minimum temperature (T_0).
3. Do the corresponding graph distance error versus temperature.
4. Find the corresponding 2nd order polynomial with the best fir to the measured data.

$$E_T = a \cdot (T - T_0)^2 - b \cdot (T - T_0)$$

5.2. Background light calibration

The intensity of the background light affects the distance measurement. However, since the background light (or also called ambient light) can be measured by the epc600/epc610 chip, the measured data can be compensated. Figure 4 shows a typical behavior of the background light effect, measured with the epc600 Evaluation Kit. For example, we measure 330cm distance at a set distance of 330cm with no background light (green curve). If we intensify the background light to 1'200 DN, which is an equivalent of approx. 80kLux on the target, the measured distance changes to almost from 330cm to 380cm.

We can see the same effect at other distances (blue and red curve in Figure 4).

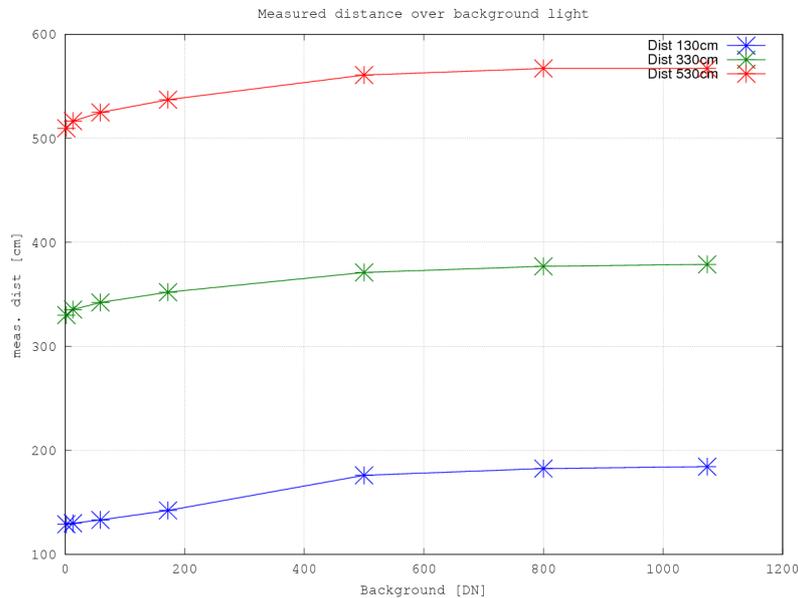


Figure 4: Distance and background level measurements
(Background 1'200 DN represents approx. 80 kLux in a given setup)

Thus, a compensation is strongly recommended in order to achieve a good distance measurement.

The following setup for a sensor with a measurement range between a few cm and 5 meters is suggested:

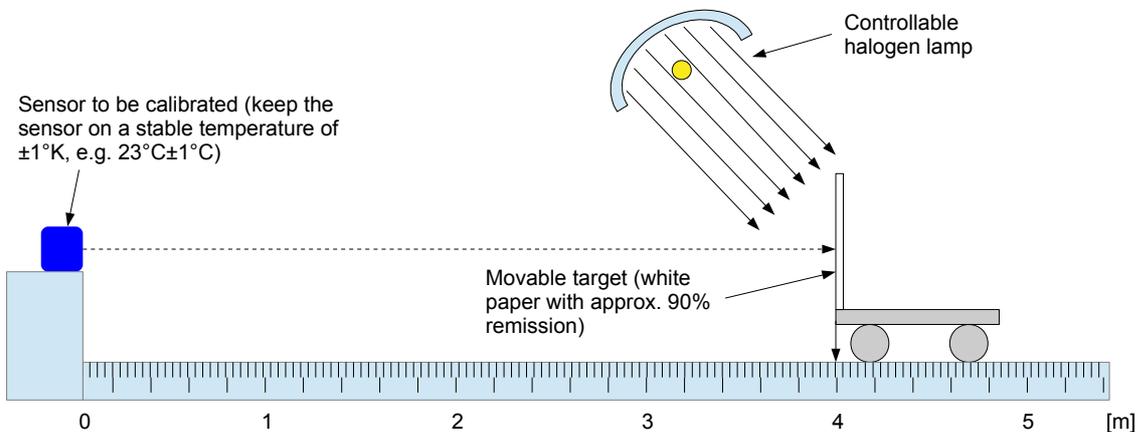


Figure 5: Setup for backlight calibration

The background light calibration procedure is achieved within the following four steps:

1. Data acquisitions
2. Data analysis
3. Linear fit of BG dependence for 2 BG regimes (B_0, B_1) and (B_1, B_2) out of 3 BG levels (B_0, B_1, B_2)
4. Linear fit of distance / phase dependence for 2 BG regimes (Distance correction for BG light)

5.2.1. Data acquisition

Measurements are taken at

- 1 fixed distance: typically between 100 to 200 cm - and
- 3 BG light levels: around 0, 500 and 1'000 DN at a BG integration time $t_{int} = 1.6\mu s$.

The BG light level (B_i) does not need to be very accurate since it will be measured with the epc600/epc610 and fitted to that data. It should be accurate by about $\pm 10\%$, but it should be stable throughout the data acquisition to $\pm 5\%$.

The distance data D_{Tcorr_i} is selected by the selection algorithm and the distance is already temperature corrected. Only data with a signal-to-BG ratio of more than 0.001 ($> -60dB$) are used in the calibration procedure.

The result of the measurement is a triple pair of two parameters: (background, measured distance) $\rightarrow B_i, D_{Tcorr_i}$.

Set distance	$D_{set} \sim 150cm$		
Set background light	$B_0 \sim 0 DN$	$B_1 \sim 500 DN$	$B_2 \sim 1'000 DN$
Measured data pair	B_0, D_{Tcorr_0}	B_1, D_{Tcorr_1}	B_2, D_{Tcorr_3}

Table 4: Distance and background level measurements

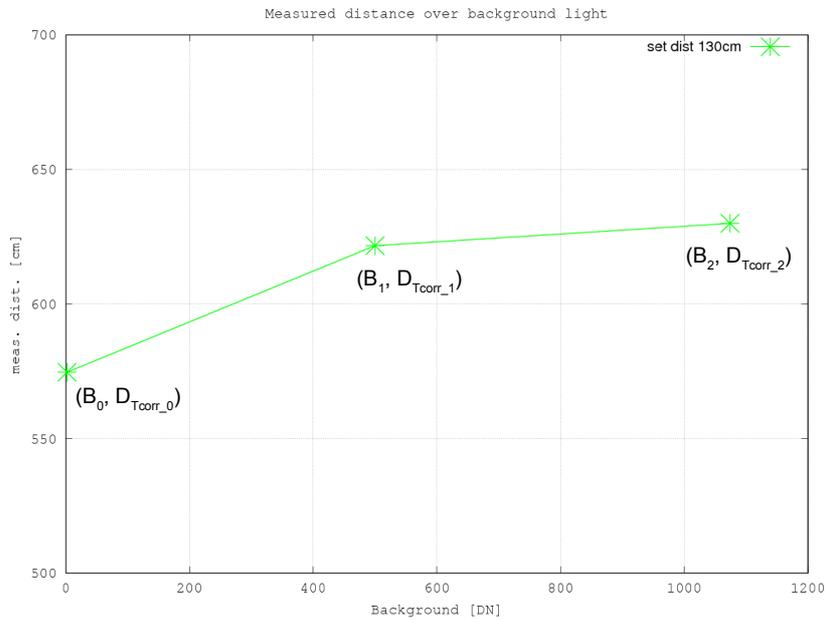


Figure 6: Distance versus background measurements

5.2.2. Data analysis

First, we calculate the distance error E_i by subtracting the measured distance D_{Tcorr_i} from the set distance D_{set} :

$$E_i = D_{Tcorr_i} - D_{set}$$

Set distance	$D_{set} \sim 150\text{cm}$		
Set background light	$B_0 \sim 0 \text{ DN}$	$B_1 \sim 500 \text{ DN}$	$B_2 \sim 1'000 \text{ DN}$
Calculated distance error E_i	$E_0 = D_{Tcorr_0} - D_{set}$	$E_1 = D_{Tcorr_1} - D_{set}$	$E_2 = D_{Tcorr_2} - D_{set}$

Table 5: Distance and background level measurements

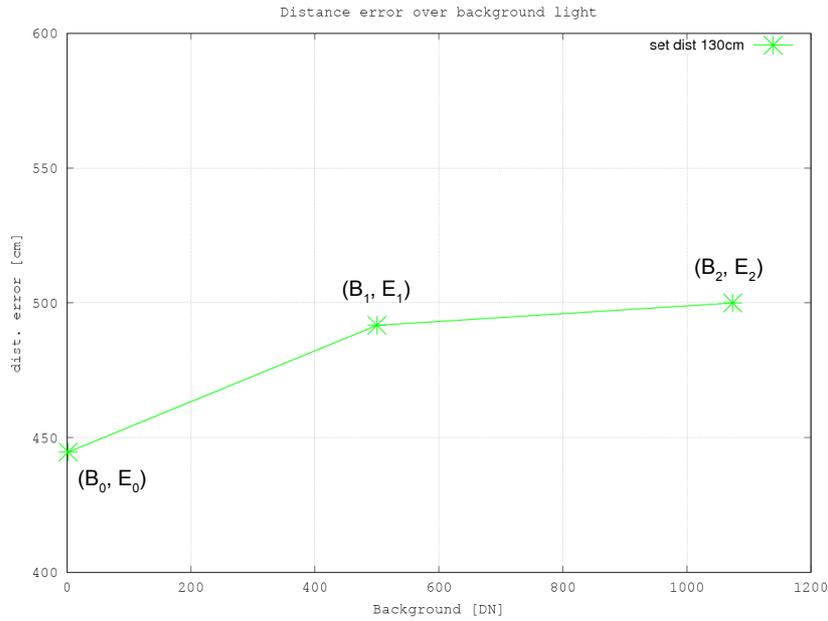


Figure 7: Distance error over background

5.2.3. Linear fit of background light level

The BG dependence of the distance error is not linear, but can be well represented by two linear fits in two different BG regimes (B_0, B_1) and (B_1, B_2). Based on the calibration measurement described above, these linear coefficients can be calculated by the linear equation:

Regime	Coefficient m_i	Coefficient k_i
$(B_0, B_1): i = 0$	$m_0 = \frac{E_1 - E_0}{B_1 - B_0}$	$k_0 = E_0 - m_0 \cdot B_0$
$(B_1, B_2): i = 1$	$m_1 = \frac{E_2 - E_1}{B_2 - B_1}$	$k_1 = (m_0 - m_1) \cdot B_1 + k_0$

Table 6: BG level coefficients

The offset error is directly corrected with the parameter k_0 . Note that k_0 can be large (several 100cm), since it covers all delays between the LED output of the chip and the illumination, e.g. caused by drivers, PCB lines, stray capacitances etc. Therefore, this parameter again is strongly system dependent.

5.2.4. Distance correction for background light

The distance can then be corrected by using the linear coefficients from above (selected by the BG regime i):

(B_i, B_{i+1}):
$$D_{Bcorr} = D_{Tcorr} - (m_i \cdot B + k_i)$$

With the temperature compensation the formula becomes:

(B_i, B_{i+1}):
$$D_{Bcorr} = D_{meas} - a \cdot (T - T_0)^2 - b \cdot (T - T_0) - (m_i \cdot B + k_i)$$

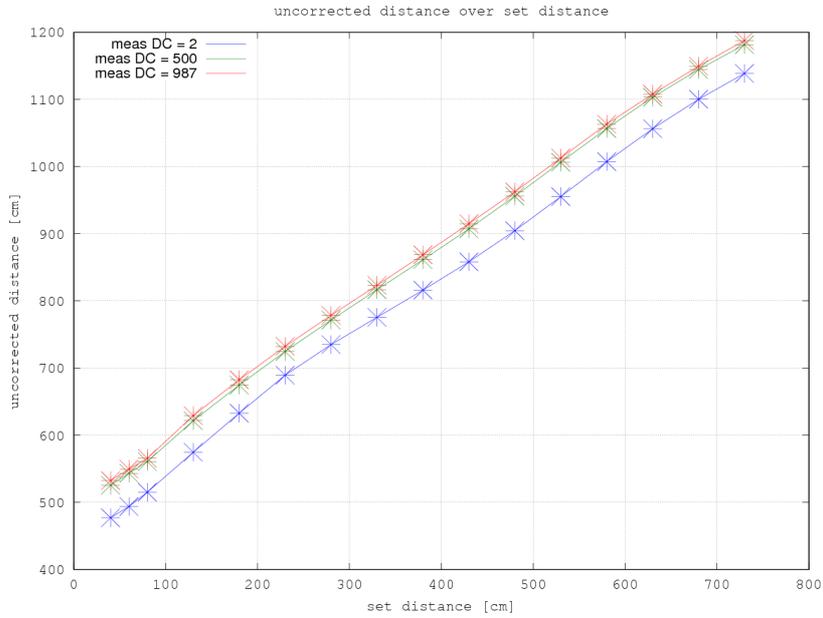


Figure 8: Uncorrected measured distance over set distance

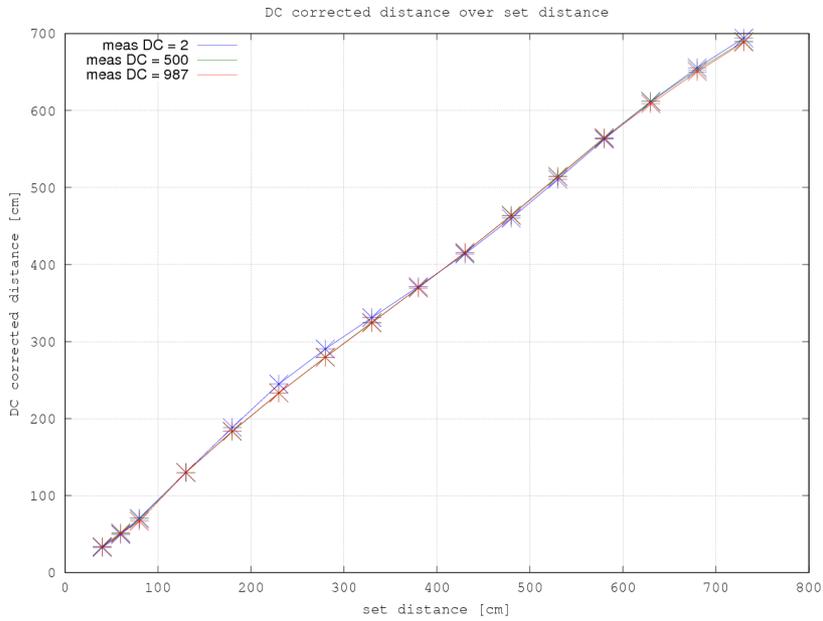


Figure 9: BG corrected measured distance over set distance

5.3. Systematic variation due to non linear signal distortions

With the methods described in the previous chapters, the influence of temperature and ambient light has been reduced to a minimum. Nevertheless, the distance output of the chip at this point will not perfectly match true distances over its operation range.

The reason for that are various effects in the chip and the sensor system which affect signal runtimes. These variations may be minuscule but given the extremely short time frames here, they are still significant (remember, a signal runtime of 1ns equals a distance traveled by light of 30cm!). The results are non-linear distance offsets over the measurement range.

In order to calibrate these systematic variations, a final lookup table approach is chosen. 16 distances are measured across the complete operating range. As we assume that BG influence is taken care of by the implemented algorithm, these measurement are taken at constant BG level, i.e. at B1 ~ 500DN. This 16 points a look-up table is then used to correct the final distance. This corrects the distance for the particular case (@ given BG) very nicely (see Figure 10).

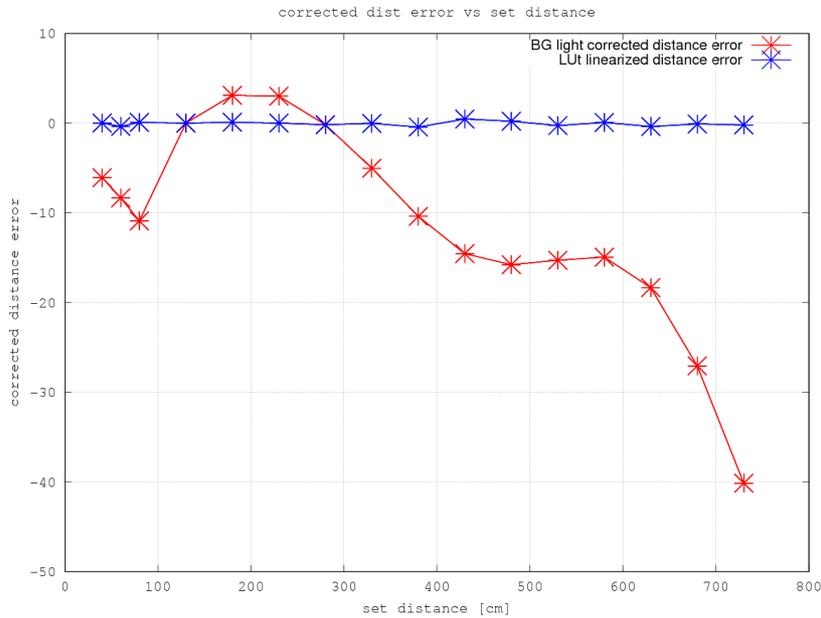


Figure 10: Post correction linearization with LUT. Background level: 500 DN

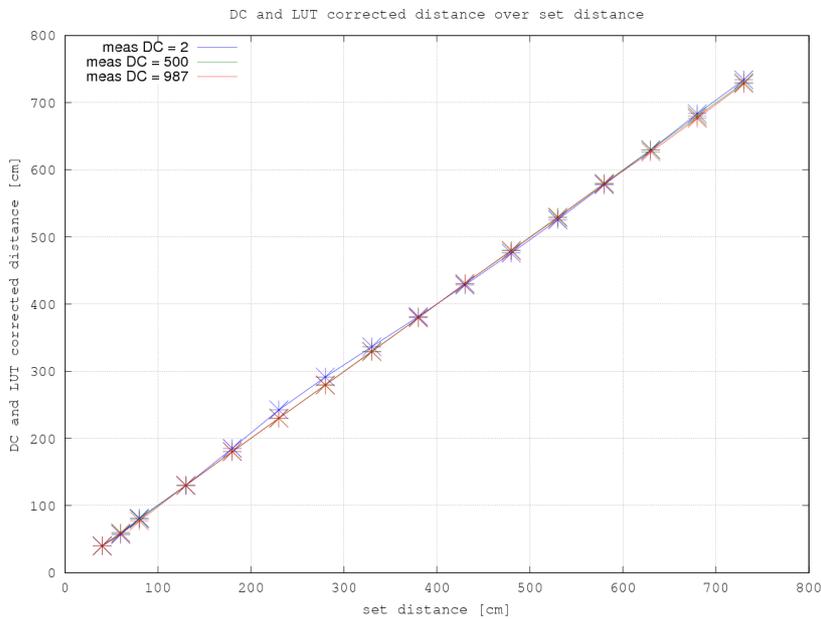


Figure 11: BG and LUT corrected distance over set distance

6. Further developments

epc is further improving the performance of the epc600/epc610 products. Therefore, absolute dependencies shown above may vary for the products delivered. Generally, we aim to minimize the effort for customer-based calibration. As soon as improved algorithms are established, we will distribute them by application note.

7. Conclusion

This paper demonstrates that with three integration time values and a useful pixel dynamic range, an overall dynamic range of approx. 76dB with 230 frames per second can be achieved for an epc600 chip. Furthermore, it shows how effective imperfections of the measurement, given by ambient influences e.g. temperature and background light, can be corrected with simple methods to achieve a fairly accurate distance information.

If you need more information, please go to www.espros.ch or contact us at info@espros.ch.

8. References

- (a) DATASHEET epc600, ESPROS Photonics corp., 2014
- (b) DATASHEET epc610, ESPROS Photonics corp., 2014
- (c) HANDBOOK ep600, ESPROS Photonics corp., 2014
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- (e) MANUAL epc610 camera, ESPROS Photonics corp., 2014

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