DATASHEET – epc660
3D TOF imager 320 x 240 pixel

General Description

The epc660 is a fully integrated 3D-TOF imager with a resolution of 320 x 240 pixels (QVGA). As a system on chip, the epc660 contains next to the CCD pixel-field the complete control logic to operate the device. The output of the chip is 12 bit DCS distance data per pixel, which are accessible through a high-speed digital 12-bit parallel video interface.

Only few additional components are needed to generate a complete 3D camera. Depending on illumination power and optical design, a resolution in the millimeter range for distances up to dozens of meters is feasible. Up to 158 full frame TOF images are delivered in rolling mode. The extremely high sensitivity of the chip allows for a reduced illumination power and reduced overall power consumption compared to other TOF imagers.

epc660 is based on the same technology and instruction set as the epc635 Half-QQVGA TOF imager from ESPROS.

An evaluation kit for the epc660 is available with hard- and software examples and a comprehensive manual to speed up system integration.

Applications

- People detection and counting
- Postal parcel size measurement
- Machine safety
- Drone near terrain flight assistance
- ADAS systems
- Pedestrian detection and breaking systems
- Man-Machine interface
- Gesture control
- Body size measurement
- General volumetric mapping
- Mobile robotics
- Simultaneous localization and mapping (SLAM)

Block Diagram

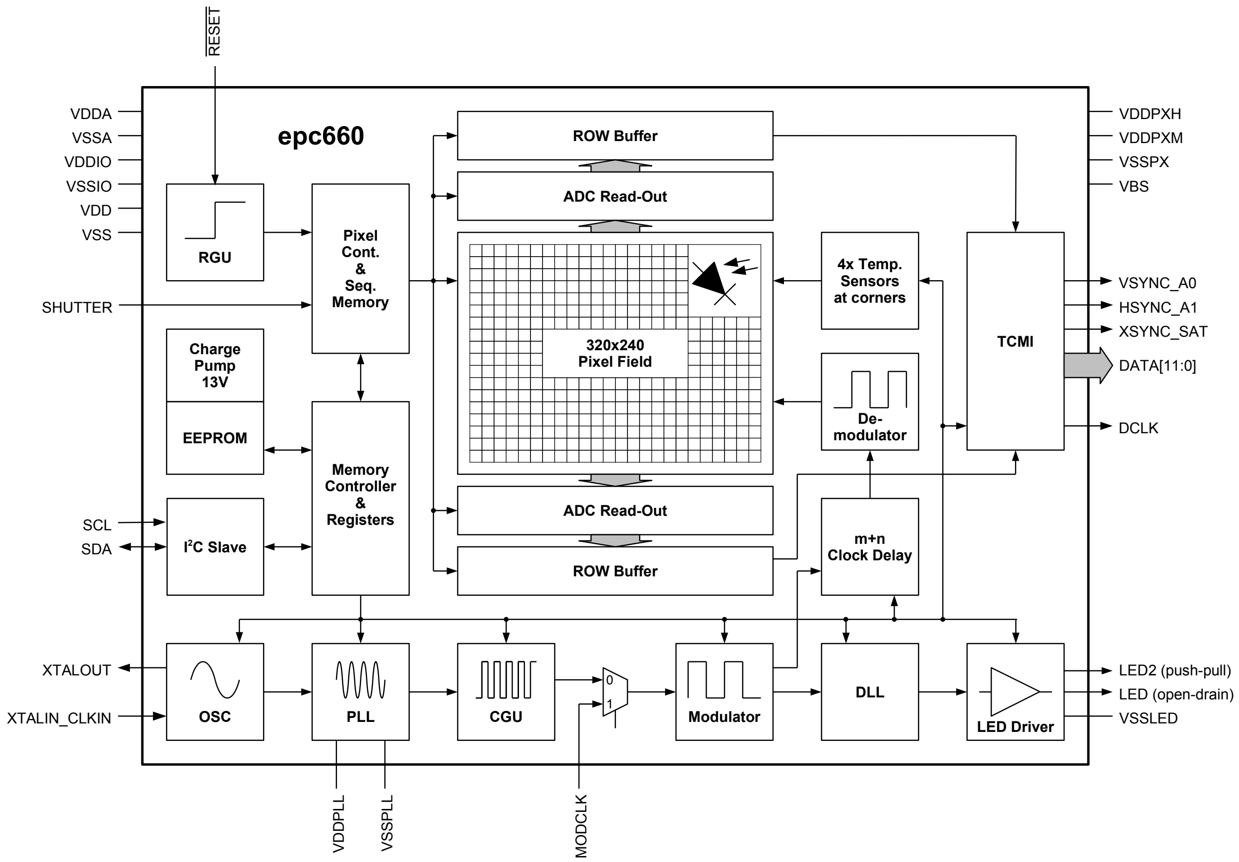

Figure 1: Functional block diagram

Main Features

- **General**
  - □ 3D TOF imager in full monolithic design
  - □ 320 x 240 pixel-field, backside illuminated
  - □ QE >80% @ 850nm
  - □ Full well capacity 8'000 ke- (ambient and signal)
  - □ 39 fps full 3D TOF frame rate, single frame rate up to 158fps
  - □ Region of interest setting allows up to several kfps
  - □ 4 integrated temperature sensors
- **Measurement performance**
  - □ Absolute accuracy in the sub-centimeter range with appropriate setup and calibration
- **Integrated LED (or laser diode) driver**
  - □ Laser diode (LD) illumination possible
  - □ Open-drain LED output pad, up to 200mA drive
  - □ Push-pull LED2 output pad, up to 50mA drive
- **Parallel digital data interface TCMI**
  - □ 48MS/s max. data rate, 2.5/3.3V compatible
  - □ 12/8-bit parallel DATA output + XSYNC/SAT flag
  - □ VSYNC, HSYNC and DCLK outputs
- **I^2C control interface (slave)**
  - □ 400kHz (FM) / 1MHz (FM+)
- **Integrated EEPROM 128 x 8-bit**
  - □ Calibration data and user programmable parameters
  - □ Unique chip ID
- **System / modulation clock**
  - □ System clock 4MHz, internal by using crystal/resonator or using external input
  - □ External LED/LD modulation input MODCLK (optional) up to 96MHz
- **Power supply**
  - □ Supply voltages +10V, +5V, +2.5/3.3V, +1.8V, -10V
  - □ Power consumption approx. 750mW (average)
- **Packaging**
  - □ 9.7x8.7mm cost optimized 68pin CSP (chip scale package),
  - □ Backside illuminated flip-chip SMD mounting
- **Other data**
  - □ ROHS compatible

Measurement Modes

- **Illumination modulation modes**
  - □ Sinusoidal modulation
  - □ Selectable modulation frequencies 0.75 ... 24MHz resulting in unambiguity distance of 6.25m … 200m
- **Distance measurement modes**
  - □ 39 fps 3D TOF with 4x DCS frames, full pixel-field
  - □ 79 fps 3D TOF with 2x DCS frames, full pixel-field
  - □ 158 fps 3D TOF with rolling read-out 4x DCS frames, full pixel-field
  - □ Ultra fast measurement by reduction of the image field (ROI)
  - □ SHUTTER release input for precise start/stop and single/continuous measurement control
- **Non distance measurement modes**
  - □ Ambient-light measurement (Grayscale image without illumination)
  - □ Grayscale image with active illumination

Readout Modes

- **ROI (Region of interest)**
  - □ Rectangular sub-pixel-field read-out
  - □ Increased frame rate
- **Binning and resolution reduction**
  - □ Binning of max. 4 adjacent pixels (2 hor. and 2 ver.)
  - □ Resolution reduction to 2nd, 4th or 8th row or column to read-out
  - □ Increased frame rate for reduced number of rows

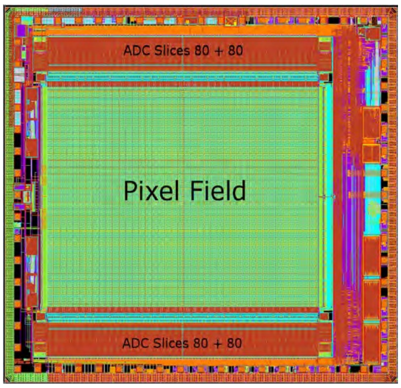

Figure 2: Picture of the epc660

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1. Electrical, optical and timing characteristics

All characteristics are at typical operational ratings, T_A = +25ºC, modulation frequency 12MHz, supply voltages at nominal value, unless otherwise stated

1.1. Operating conditions and electrical characteristics

Parameter	Description	Conditions/Comments	Min.	Typ.	Max.	Units
V_{DD},V_{DDPLL}	Digital supply voltage	Ripple [1] < ± 20 mV	1.71	1.80	1.98	V
V_{DDIO}	IO supply voltage [3]	Ripple [1] < ± 50 mV	2.25	2.5/3.3	3.63	V
V_{DDA}, V_{DDPXM}	Analog 1 supply voltage [2]	Ripple [1] < ± 20 mV	4.9	5.0	5.1	V
V_{DDPXH}	Analog 2 supply voltage [2]	Ripple [1] < ± 20 mV	9.5	10	10.5	V
V_{BS}	Bias supply voltage	Ripple [1] < ±50 mV	-10.5	-10.0	-9.75	V
I_{VDD}	Total digital supply current, including PLL supply current			14	20	mA
I_{VDDPLL}	PLL supply current			4		mA
I_{VDDIO}	IO supply current [4]			8		mA
I_{VDDA}	Analog supply current	refer to chapter 11.5		125	350	mA
I_{VDDPXM}	Analog 1 supply current			1		mA
I_{VDDPXH}	Analog 2 supply current			13		mA
I_{VBS}	Bias supply current [8]			3.8 [8]		mA
V_{LED_ON}	LED on-voltage forward voltage	@ $I_{LEDOD\text{-}ON}$ = 100 mA @ $I_{LEDOD\text{-}ON}$ = 200 mA		0.1 0.2		V V
I_{LED_LEAK}	LED leakage current	@ LEDOD off-voltage			10	µA
I_{LED2_SINK}	LED2 output sink/source current				50	mA
V_{IH_VDDIO}	Digital high level input voltage [5]	excluding XTALIN	0.7 x V_{DDIO}			V
V_{IL_VDDIO}	Digital low level input voltage [5]	excluding XTALIN			0.3 x V_{DDIO}	V
V_{IH_XTALIN}	Digital high level input voltage	XTALIN	1.35			V
V_{IL_XTALIN}	Digital low level input voltage	XTALIN			0.2	V
V_{OH}	Digital high level output voltage [5, 6]		0.8 x V_{DDIO}			V
V_{OL}	Digital low level output voltage [5, 6]				0.2 x V_{DDIO}	V
R_{PD}	Pull-down resistor in RESET, VSYNC_A0, HSYNC_A1			600		kΩ
I_{IH}	Digital high level input current [7]	V_{IH} max.			10 [7]	µA
I_{IL}	Digital low level input current [7]	V_{IL} min.	-10 [7]			µA
I_{OH}	Digital output source current [7]	V_{OH} max.			50	mA
I_{OL}	Digital output sink current [3]	V_{OL} min.	-50			mA
C_{IO}	IO load capacitance [5]				30	pF
f_{IO}	IO switching frequency [5]			24	48	MHz
P_{Pk}	Power dissipation (average)	See Table 30		750		mW
R_{Th}	Thermal resistance	on PCB with underfill			40	°K/W
T_{OP}	Operating temperature		-40		105	°C

Table 1: Operating conditions and electrical characteristics

Notes:

[1] Min. and Max. voltage values include noise and ripple voltages.

[2] Analog voltage supplies have direct influence on measurement performance. They must be properly decoupled for low noise and ripple.

[3] IO voltage supply must be equal to external processor's IO supply voltage levels used in the application. It can be set to any value within min and max. operating voltage.

[4] When device is operated at max f_{DCS} frame rate, DCLK at 48MHz, driving loads 15pF each.

[5] I²C pins SCL and SDA are open-drain outputs and need termination (pull-up resistor) according to I²C standards.

[6] $V_{OH/OL}$ and $I_{OH/OL}$ values are measured at max C_{IO} and max f_{IO}.

[7] Value is without termination resistors

[8] A bright illuminated white target right in front of the chip with lens leads to an I_{VBS} of approx. 3.8 mA, without any illumination approx. 3.6 mA and with strong illumination (approx. 55 mW/cm², no lens) typ. 17 mA.

1.2. Absolute maximum ratings

Parameter	Conditions
Supply voltage V_{DD}, V_{DDPLL}	-0.5V ... +2.0V
Supply voltage V_{DDIO}, V_{DDA}, V_{DDPXM}	-0.5V ... +5.5V
Supply voltage V_{DDPXH}	-0.5V ... +13.5V
Supply voltage V_{BS}	-12.0 ... +0.5V
Voltage to any pin in the same V_{SC} supply class.	$V_{SC\ min}$ - 0.3V … $V_{SC\ max}$ + 0.3V
LED sink current I_{ON_LED} (modulated peak current, refer to Figure 18)	200 mA @T_J 85°C 25 mA @T_J 125°C linear reduction between 85 and 125°C
LED off-voltage V_{OFF_LED} (open-drain output)	7.5 V
ESD rating	JEDEC HBM class 1C (1kV to < 2kV)
Junction temperature (T_J)	-40°C to +125°C
Relative humidity	0 ... 95%, non-condensing

Table 2: Absolute maximum ratings

1.3. Timing parameters

Parameter	Description	Conditions	Min.	Typ.	Max.	Units
$t_{STARTUP}$	Start-up time	after applying external supplies		340	1'000	µs
$t_{\overline{RESET}}$	$\overline{\text{RESET}}$		100			ns
$t_{PLLStrap\_scan}$	Scanning strap pins			4x osc_clk		
t_{PLL}	PLL lock time				30	µs
t_{DLL}	DLL delay for 1 step	approx. 30cm distance shift per step. Refer for details to register 0x73 and Figure 23, for exact value to register 0xE9.		2.1		ns
t_{DRV}	Illumination driver delay	delay of LED/LED2 versus demodulation, refer to Figure 59		8.4		ns
$t_{EEPROM\_to\_CFG}$	Load CFG registers	copy EEPROM to CFG registers		340		µs
t_{EEPROM_Write}	Write EEPROM	waiting time per byte			25	ms
f_{XTAL}	Clock frequency	determines the distance measurement accuracy	3.8	4	4.2	MHz
df_{XTAL}	Clock frequency deviation	any deviation is added as a linear distance error			±100	ppm
f_{JITTER}	Clock frequency phase jitter	peak-to-peak, cycle to cycle			50	ps
f_{LED}	LED modulation frequency		0.75		24	MHz
f_{MODCLK}	Ext. modulation clock	refer to chapter 5.5			96	MHz
$t_{LED\_rise/fall}$	Rise/fall time LED/LD				12	ns
f_{DCLK}	TCMI pixel rate	12 bit pixel data + saturation flag		24	48	MHz
f_{TCMI_data}	TCMI data rate			312	624	Mbit/s
f_{SCL}	I^2C data rate				1	Mbit/s

Table 3: Timing parameters

1.4. Optical characteristics

Parameter	Description	Conditions/Comments	Value	Units
A_{PIXEL}	Pixel photosensitive area	100% fill factor	20 x 20	µm
A_{SENSOR}	Pixel-field area	320 x 240 pixel	6.4 x 4.8	mm

Table 4: Optical characteristics

1.5. Sensitivity

@ integration time 100 µs

Parameter	Description		Min.	Typ.	Max.	Units
TOF sensitivity S_{TOF}	• Modulation frequency 12MHz • Amplitude 1,400 LSB	640nm	0.75	0.9	1.05	$\frac{nW/mm^2}{LSB}$
		850nm	0.50	0.6	0.70	
		940nm	0.65	0.8	0.95	
TOF_{SENS} FPN	Sensitivity fix pattern noise, @ 1,400 LSB			40	100	LSB
TOF_{DIST} FPN	Distance fix pattern noise, @ 1,400 LSB			18	50	mm
I_{Dark}	Dark current (drift during readout)			10	20	LSB/ms
Grayscale sensitivity	Normal operation		0.19	0.25	0.31	$\frac{nW/mm^2}{LSB}$
	Temperature sensing mode		0.48	0.62	0.76	
H_v	Optical sensitivity			150k		$\frac{LSB}{Lux/sec}$
GS_{STD}	Grayscale standard deviation			25	100	LSB

Table 5: Sensitivity

1.6. Ambient-light suppression (ABS)

An important function of the 3D TOF pixel is the ambient-light suppression. It removes DC or low frequency modulated light caused by sunlight, room illumination, etc. from the modulated light generated by the camera illumination. The amount of collected ambient light is proportional to the integration time. The longer the integration time, the more unwanted light will be collected. It's a good practice to keep the integration time for TOF imaging below 1ms. In addition, optical bandpass filters to block the unwanted light spectrum is mandatory.

Parameter	Ambient light suppression	Integration time	Wave-length	Min.	Typ.	Max.	Units
E_e	Irradiance, DC light	100 µs	640nm	0.30			mW/mm^2
			850nm	0.20			
			940nm	0.25			

Parameter	Ambient light suppression	Integration time	Center wavelength	Bandwidth	Min.	Typ.	Max.	Units
E_v	Luminance equivalent, sunlight	500µs	640nm	±27.5nm	85			kLux
			850nm	±32.5nm	70			
			940nm	±30nm	190			

Table 6: Ambient light suppression

Note:
The default and suggested chip configuration is set to achieve highest possible frame rate and using additional ambient-light correction according the Application note AN10 Calibration and compensation: Register 0x90, bit 3 = 0 and 0xAB = 0x00. A 20% more efficient ambient-light suppression is possible, if the the following registers are modified:

0x90, bit 3 = 1

0xAB = 0x01

It turns the LED modulation before each integration for additional 33µs @ 24MHz modulation frequency on. This modulation is independent of the effective integration time. The on-time depends on the modulation frequency by t_{ON} = 40µs * 20MHz / modulation frequency.

1.7. Other optical parameters

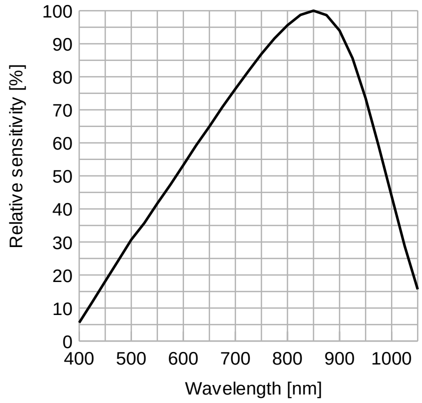


Figure 3: Relative spectral sensitivity (S_λ) vs. wavelength

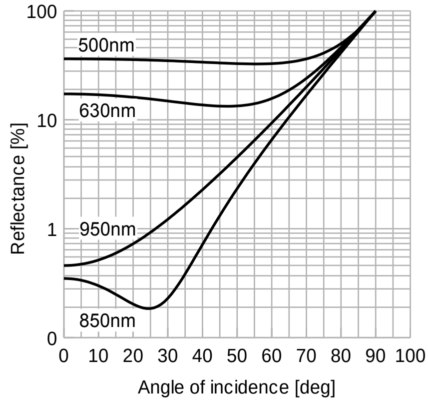


Figure 4: Reflectance vs. illumination angle (AOI)

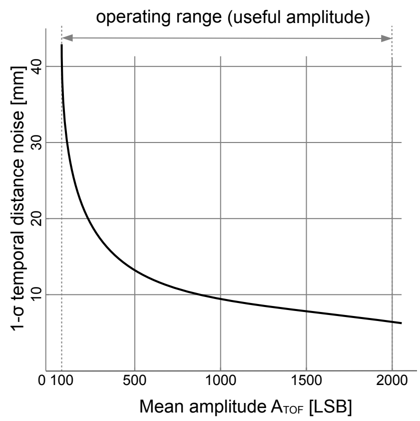


Figure 5: Typ. distance noise, single shot, 4 DCS, no ambient-light, see chapter 9.2.2

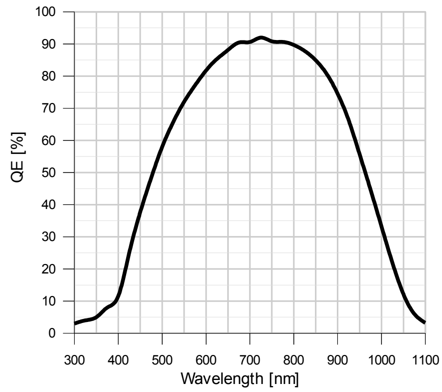


Figure 6: Typical quantum efficiency

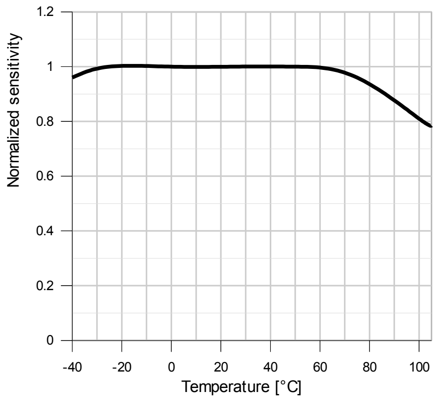


Figure 7: Typical TOF sensitivity temperature coefficient

1.8. Temperature sensor characteristics

Parameter	Description	Conditions	Min.	Typ.	Max.	Units
T_{TEMP}	Measurement range		-40		+105	ºC
P_{TEMP}	Sensor resolution			14		bit
k	Temperature sensor gain			0.067		K/LSB
Lin	Linearity	Over temperature range		5		%
T_{CAL}	Calibration temperature		26.5	27.0	27.5	°C

Table 7: Temperature sensor characteristics

Note: Refer also to chapter 10.

1.9. Distance measurement temperature drift

@12MHz modulation frequency

Parameter	Description	Min.	Typ.	Max.	Units
TC_{PIX}	Pixel		11.3		mm/K
TC_{OD}	LED/LD driver		2.7		mm/K
TC_{DLLn}	DLL stage, per stage		0.65		mm/K

Table 8: Optical characteristics

Note: Values vary from imager to imager. Refer for details to Figure 22 and application note AN10 Calibration and Compensation, chapter temperature compensation.

2. Pin-out

2.1. Pin mapping

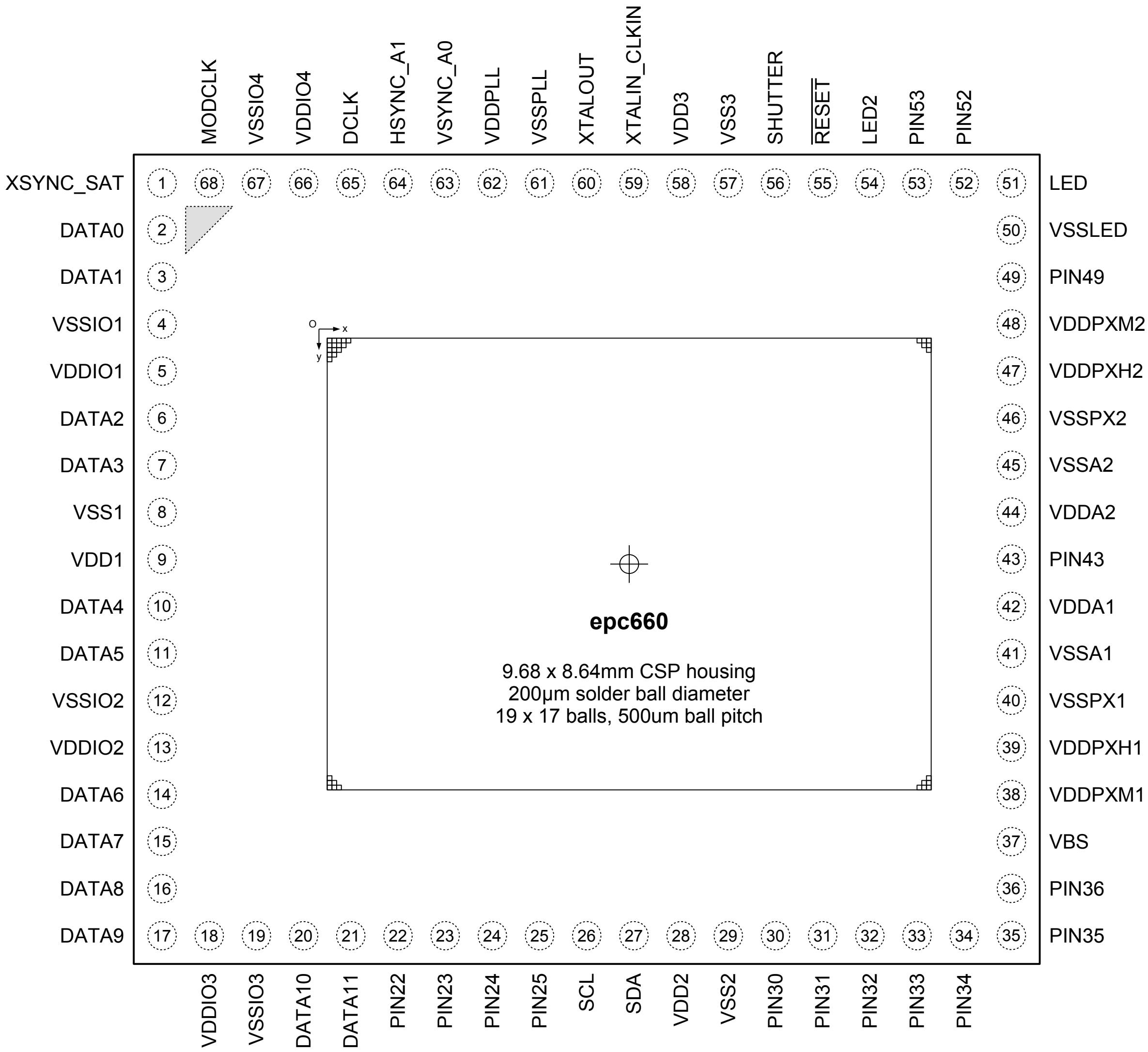


Figure 8: CSP pin mapping (top-view, solder balls are at the bottom, pixel-field is at the top)

2.2. Pin list

Pin No.	Pin name	Supply class V_{SC}	Pin type	RESET function	RESET level	Description
IO pins						
2	DATA0	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 0, no pull-up resistor allowed.
3	DATA1	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 1
6	DATA2	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 2
7	DATA3	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 3
10	DATA4	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 4
11	DATA5	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 5
14	DATA6	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 6
15	DATA7	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 7

Table 9: Pin list

Pin No.	Pin name	Supply class V_{SC}	Pin type	RESET function	RESET level	Description
16	DATA8	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 8
17	DATA9	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 9
20	DATA10	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 10
21	DATA11	V_{DDIO}	DIO	IPD	V_{OL}	TCMI high-speed output bit 11
65	DCLK	V_{DDIO}	DIO	IPD	V_{OL}	TCMI data clock output
63	VSYNC_A0	V_{DDIO}	DIO	IPD	V_{OH}	TCMI VSYNC output / strap input 0, refer to chapter 5.6.3
64	HSYNC_A1	V_{DDIO}	DIO	IPD	V_{OH}	TCMI HSYNC output / strap input 1, refer to chapter 5.6.3
1	XSYNC_SAT	V_{DDIO}	DIO	IPD	V_{OH}	TCMI XSYNC / TCMI saturation flag output, no pull-up resistor allowed.
26	SCL	V_{DDIO}	DIOD	I	V_{IH}	I²C clock input [4]
27	SDA	V_{DDIO}	DIOD	I	V_{IH}	I²C data input/output [4]
56	SHUTTER	V_{DDIO}	DI	PD	V_{IL}	Shutter input [5]
55	$\overline{\text{RESET}}$	V_{DDIO}	DI	PD	V_{IL}	Reset input (active low), 600kΩ int. pull-down [3]
68	MODCLK	V_{DDIO}	DI	PD		Modulator/demodulator external clock input.
54	LED2	V_{DDIO}	DO			LED driver push-pull output [2]
22	PIN22	---	DO		V_{OL}	Do not make any electrical connection except to a test pad.
23	PIN23	---	DI	PU	V_{IH}	
24	PIN24	---	DI	PD	V_{IL}	
25	PIN25	---	DI	PU	V_{IH}	
Digital pins						
59	XTALIN_CLKIN	V_{DDPLL}	AI			XTAL or Resonator in / CLKIN from external clock source
60	XTALOUT	V_{DDPLL}	AO			XTAL or Resonator out
Analog pins						
51	LED	V_{DDLED}	AOD		V_{LED} max	LED/LD driver open-drain output [2]
35	PIN35	V_{DDPXH}	---			Connect to VSSPX with 10 kOhm
36	PIN36	V_{DDPXH}	AI			
31	PIN31	---	AI			Do not make any electrical connection except to a test pad.
32	PIN32	---	AI			
33	PIN33	---	---			
34	PIN34	---	---			
49	PIN49	---	AI			Connect to ground with a 10kΩ resistor
52	PIN52	---	---			Do not make any electrical connection except to a test pad.
53	PIN53	---	---			
Supply pins, digital						
5	VDDIO1	V_{DDIO}	PWR			IO supply VDDIO
13	VDDIO2	V_{DDIO}	PWR			
18	VDDIO3	V_{DDIO}	PWR			
66	VDDIO4	V_{DDIO}	PWR			
9	VDD1	V_{DD}	PWR			Digital supply VDD
28	VDD2	V_{DD}	PWR			
58	VDD3	V_{DD}	PWR			
62	VDDPLL	V_{DDPLL}	PWR			PLL supply
4	VSSIO1	V_{DDIO}	GND			IO ground VSSIO
12	VSSIO2	V_{DDIO}	GND			
19	VSSIO3	V_{DDIO}	GND			
67	VSSIO4	V_{DDIO}	GND			

Table 9 cont.: Pin list

Pin No.	Pin name	Supply class V_{SC}	Pin type	RESET function	RESET level	Description
8	VSS1	V_{DD}	GND			Digital ground VSS
29	VSS2	V_{DD}	GND			
57	VSS3	V_{DD}	GND			
61	VSSPLL	V_{DDPLL}	GND			PLL ground
Supply pins, analog						
42	VDDA1	V_{DDA}	PWR			Analog supply VDDA
44	VDDA2	V_{DDA}	PWR			
37	VBS	V_{BS}	PWR			Bias supply
39	VDDPXH1	V_{DDPXH}	PWR			Pixel analog 2 supply VDDPXH
47	VDDPXH2	V_{DDPXH}	PWR			
38	VDDPXM1	V_{DDPXM}	PWR			Pixel analog 1 supply VDDPXM
48	VDDPXM2	V_{DDPXM}	PWR			
41	VSSA1	V_{DDA}	GND			Analog ground VSSA
45	VSSA2	V_{DDA}	GND			
40	VSSPX1	V_{DDPX}	GND			Pixel analog ground VSSPX
46	VSSPX2	V_{DDPX}	GND			
50	VSSLED	V_{DDLED}	GND			LED/LD driver ground (return current) [1]
30	PIN30	V_{PIN35}	PWR			Connect to VSS
43	PIN43	V_{PIN43}	PWR			Connect to VDDA

Table 9 cont.: Pin list

Notes:

[1] VSSLED is the dedicated, isolated GND pin for the LED/LD return-current from external circuitry. It must be connected to PCB GND plane together with the other VSSA GND pins.

[2] LED output can be used to drive an external amplifier with an addition of a pull-up resistor. The voltage at LED output pin must not exceed value in Table 1: Operating conditions and electrical characteristics.

LED2 output is a push-pull driver for delivering symmetric rise/fall times to the external LED driver circuit. LED2 is internally connected to VDDIO/VSSIO supplies. During integration time, all TCMI pins are silent except for DCLK. As a result, LED2 pin will not pick up switching noise from all other TCMI pins but the layout has to take care of the DCLK line.

LED and LED2 must not be used simultaneously for driving LED circuits on the PCB. They exhibit different insertion delays and may cause unpredicted distance offset/measurement results.

[3] RESET pin has a 600kΩ (typical) internal pull-down resistor. Therefore, this pin can be safely connected to a standard GPIO of a CPU which is initially high-Z or open-drain during power up sequence. Once the SW takes control, it can program this GPIO as output and drive 1 to release the RESET. The internal pull-down can be override by and external 10kΩ pull-up and a series capacitor to build a simple delayed power-on reset for evaluation/qualification purposes.

[4] I^2C pins SCL, SDA are according to I^2C standards. They are I^2C slave pins which need external pull-up resistors on the PCB. Values of R1 and R2 in the schematics are given only for indicative purposes and must be re-calculated according to the total capacitive load of all I^2C slave/master devices and operating mode (FM or FM+) of the I^2C (chapter 13) in the application.

[5] If HW shutter is not used, connect this pin to GND

'Pin type' in Table 9 defines the following:

- DI: Digital Input
- DO: Digital Output
- DIO: Digital Input/Output (bidirectional)
- DIOD: Digital Input/Output (bidirectional), open-Drain
- AI: Analog Input
- AO: Analog Output
- AOD: Analog Output, open-Drain
- PWR: Supply
- GND: Ground

'Rst. Func.' in Table 9 defines the function of IO pins during reset:

- I: Input
- PU: internal Pull-Up
- PD: internal Pull-Down
- IPD: Input with internal Pull-Down

'Rst. Level' in Table 9 defines the level of the IO pins during/after reset (chapter 5.6)

2.3. Power domain separation and ESD protection

The epc660 chip has internally 10 different power domains and 6 ground references which are interconnected with ESD protection diodes. All pins are also equipped with ESD protection diodes. The diodes have a breakthrough voltage of 0.3V. The designer has to take care that none of these diodes become conductive either at power-up, power-down or normal operation.

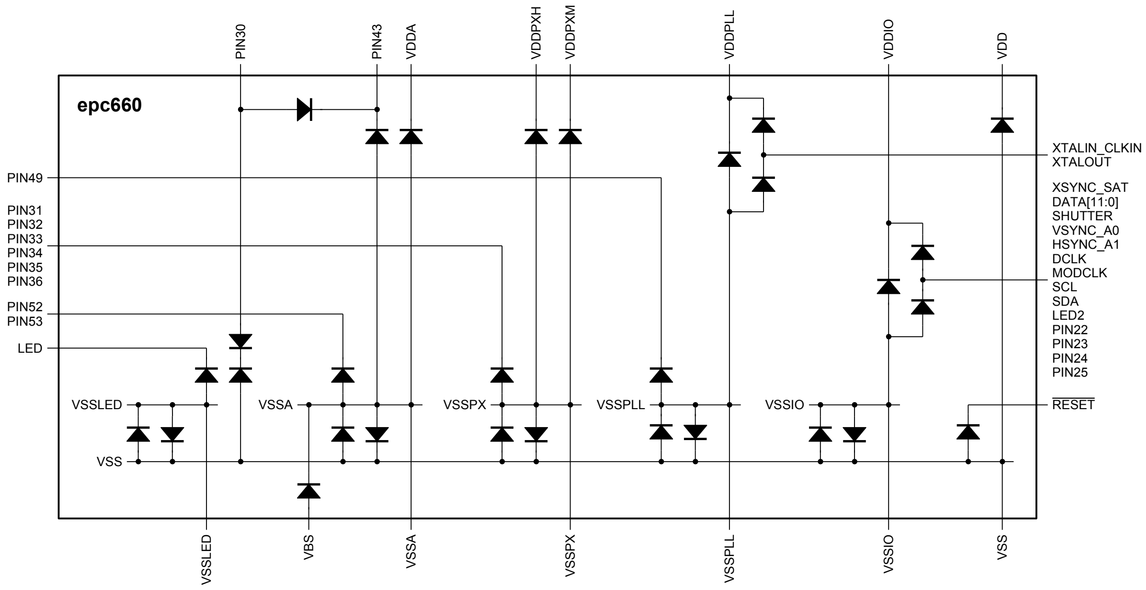


Figure 9: I/O pins and ESD protection diagram

3. Packaging and layout information

3.1. Mechanical dimensions

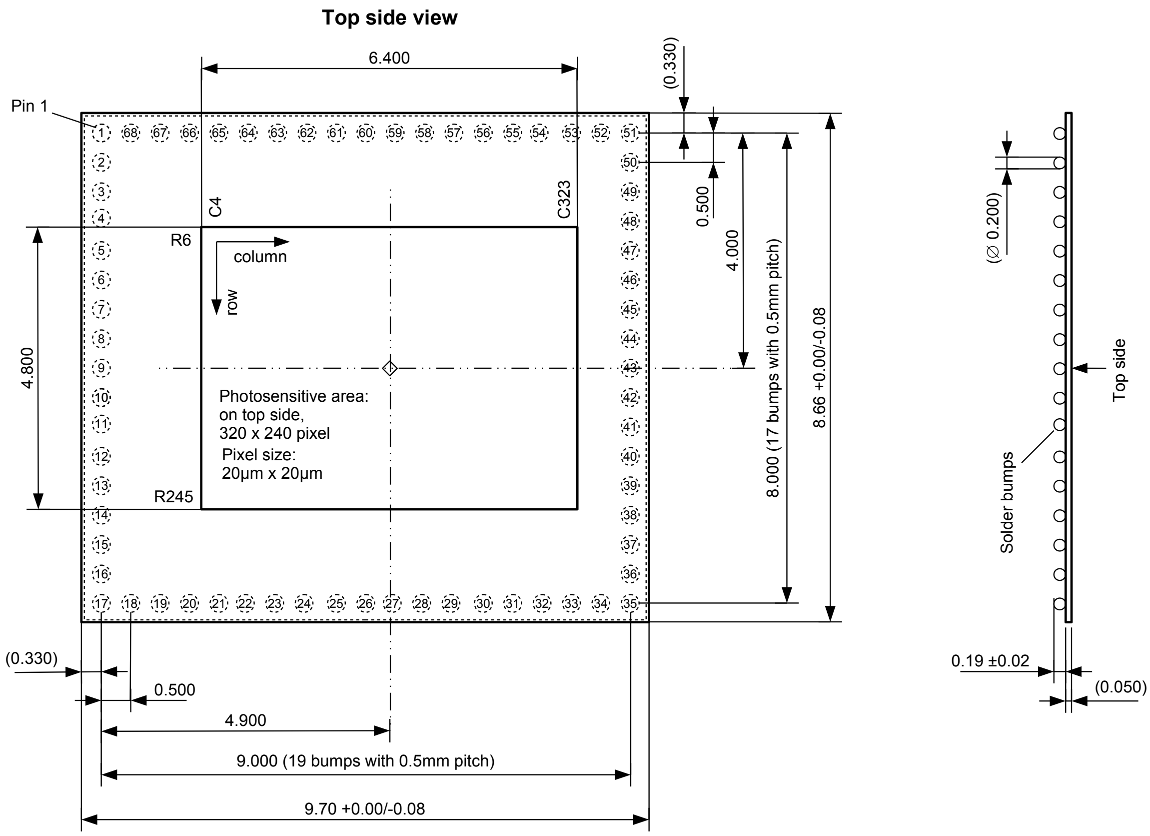


Figure 10: Mechanical dimensions

Notes:

- all measures in mm
- not specified tolerances: ±0.001mm
- Dimensions in brackets informal only
- Top side is illumination side

3.2. Parasitic light sensitivity (PLS)

CMOS circuits are sensitive to light. That is why they can be used for photo-sensing, imaging, etc. However, if strong light is radiating the chip beside the pixel field, analog and digital circuits can be affected in its function by such parasitic light. It is called parasitic light sensitivity (PLS). A known effect is a shift of the measured distance under strong ambient light. Imager lenses have always a larger field of view than the pixel-field area. In order to prevent the chip being illuminated by strong ambient light, an opaque aperture should be placed onto the photosensitive side of the imager as shown in Figure 11. The cover shall have a opening of 6.690 x 5.090 mm. With regard to the 6.400 x 4.800 mm pixel-field size, this shield can be assembled with a tolerance of ±120 µm in x and y axis. Such a cover can be made by a thin sheet metal stencil like an SMD solder paste printing stencil or by silk screen printing of black color.

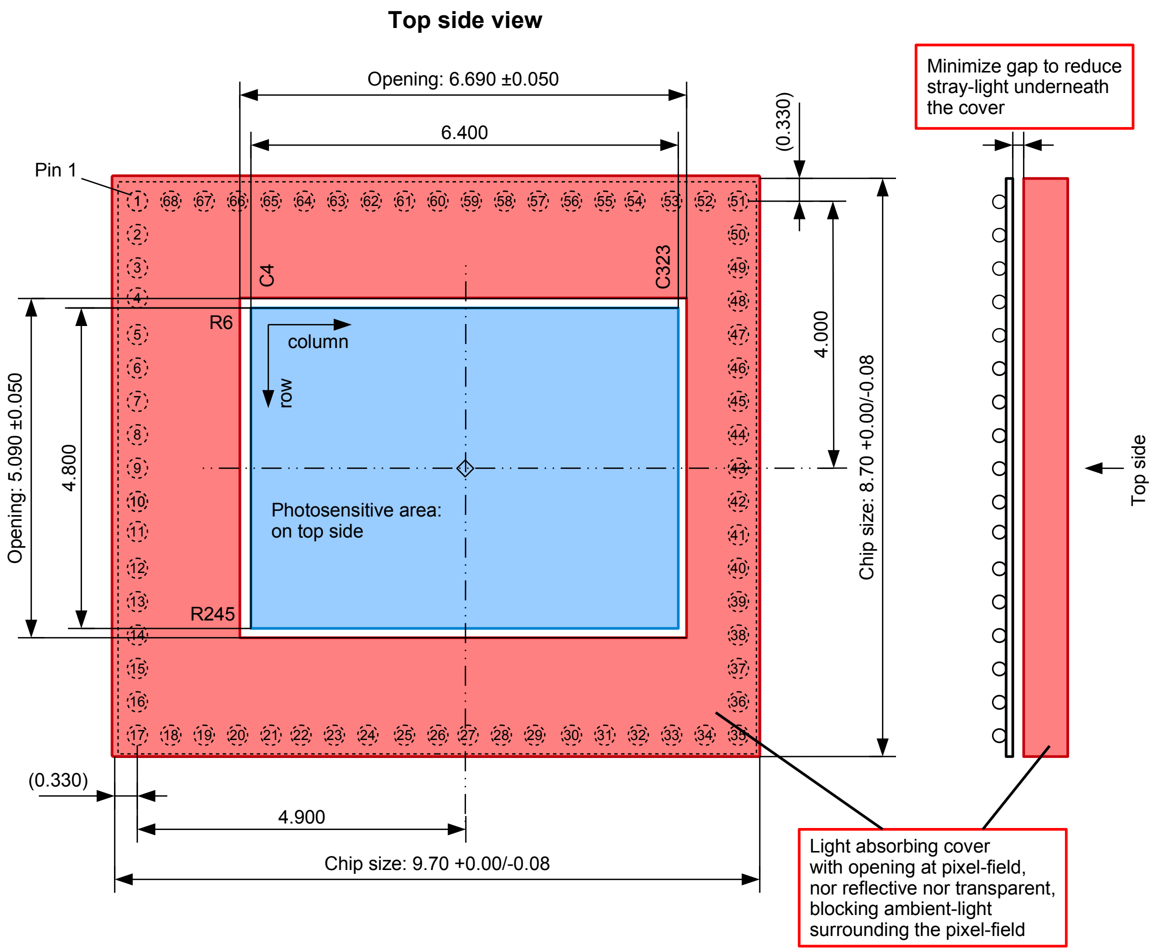
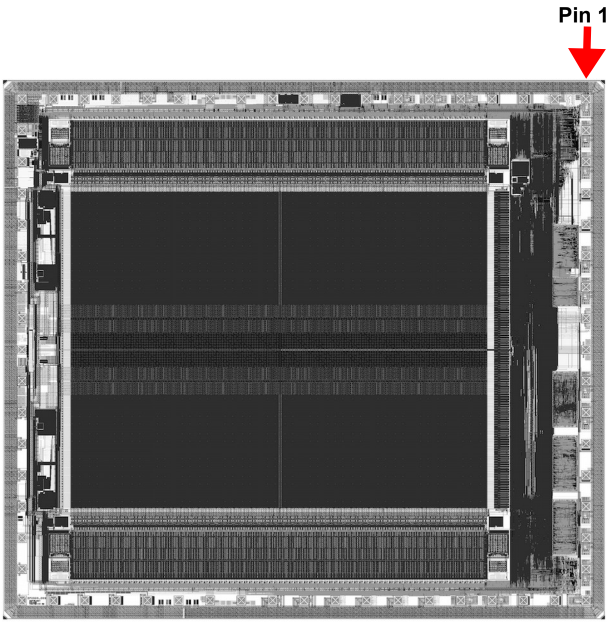


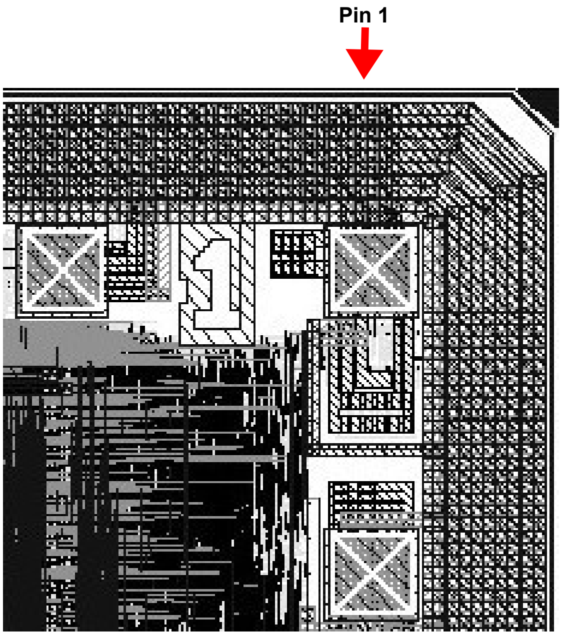
Figure 11: Opaque cover for protection against unwanted ambient-light

3.3. Pin1 marking

The following pictures shows the epc660 chip from the bottom side with view to the solder balls. Please note the location of pin 1. It's highly recommended to check the pin 1 orientation with a vision system during the SMT assembly process.



epc660 chip from the solder ball side



Top right corner from the solder ball side

Figure 12: Pin 1 marking

3.4. Location of the photosensitive area

The photosensitive area is not marked neither on the front nor on the backside of the IC. As a visible reference, a metal ring of the IC can be used. From the solder ball side it is visible. Also from the front side (photosensitive area) it can be seen with a camera which is sensitive in the near infrared wavelength domain (950 .. 1'150nm).

3.5. PCB design and SMD manufacturing process considerations

As the epc660 chip comes in a 68 pin chip scale package with only 50µm thickness, the PCB layout should be made with special care. In addition, careful handling during the assembly process shall be assured in order to avoid mechanical damage during the assembly process. Because the silicon chip is small and light weight compared the solder balls, it is highly recommended that all tracks to the chip should come straight from the side. A symmetrical design is highly recommended to achieve high production yield. The pads and the tracks should also have exactly the same width at least for 1mm from the pad. They shall be covered by a solder resist mask in order to avoid drain of the solder tin alloy to the track.

As shown in Figure 13, a ground plane shall be placed on the top PCB layer underneath the chip. This ground plane is the common GND point and acts as a shield to suppress high frequency emission of fast interface signal lines. It is important that this plane is completely flat. Thus, the plane must not be scattered nor divided into sections. It should be rather full-faced and evenly plane for vias placed underneath this plane. Otherwise chip bending might occur. In addition, the ground plane helps to dissipate the heat generated by the chip operation. A good heat dissipation is achieved if there is a temperature increase of the chip under normal operation of max. 20K. The temperature can be read direct from the chip.

Underfill of the component reduces stress to the solder pads caused by e.g. temperature cycling or mechanical bending. Furthermore the thermal and mechanical fatigue will be reduced and the longterm reliability will be increased. Underfill material and underfill selection is application specific. It shall follow JEDEC-STD JEP150: Stress-Test-Driven Qualification of and Failure Mechanisms Associated with Assembled Solid State Surface- Mount Components. Please also, refer to the application note AN08 Process-Rules CSP Assembly which can be downloaded from the ESPROS Website at www.espros.com, section Downloads. Obeying these recommendations is very important to achieve a high manufacturing yield and high reliability.

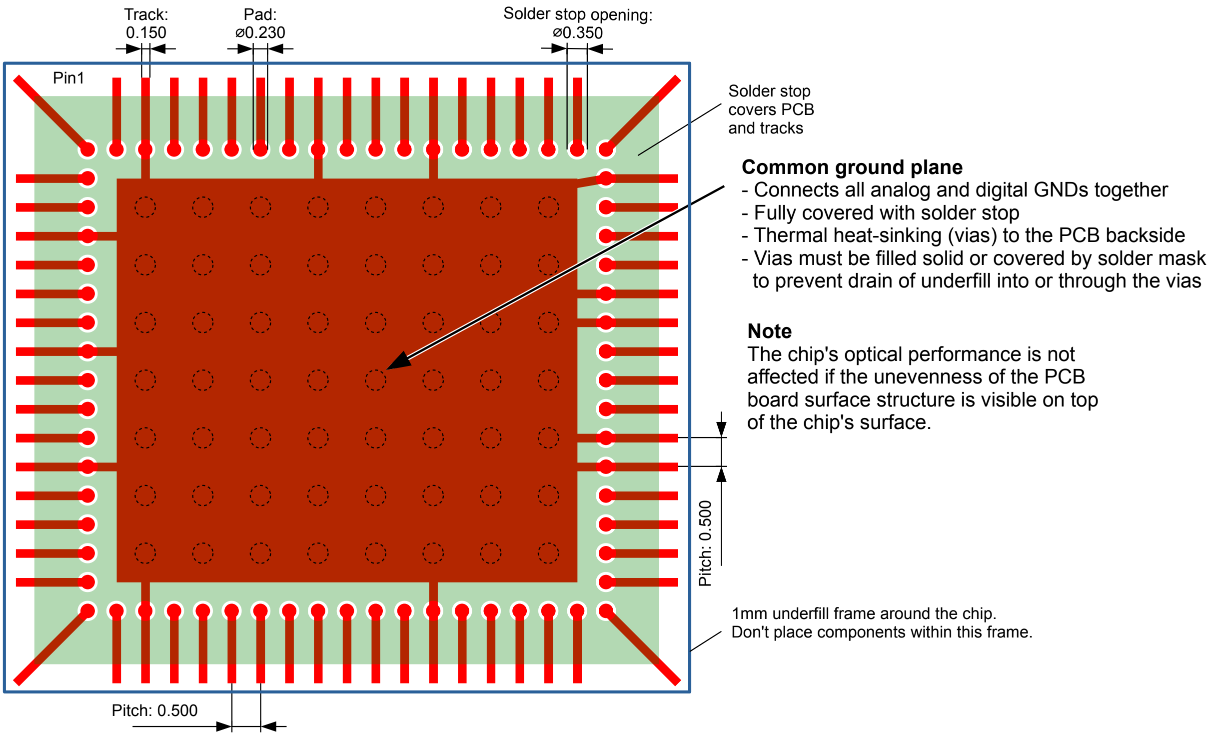


Figure 13: Recommended PCB layout (all measures in mm)

3.6. Packaging information

The devices will be shipped in standard JEDEC trays for automatic placement systems. General tray specification data are available in a separate datasheet. Further tray specifications can be found in the JEDEC Association standard JEP95.

The chips are placed according industry standard with pin 1 at the tray chamfer corner, refer to Figure 14. ESPROS does not guarantee that there are no empty cavities. Thus, the pick-and-place machine should check the presence of a chip during picking. In addition, it should verify the correct location of pin 1 (refer to Figure 12).

The trays are designed for vacuum pick-up and for a maximum temperature of 150°C.

Trays are packed and shipped in multiples of single trays with an empty cover tray on top. Trays are not a hermetic packaging. Thereof for storage and transportation, the tray stack is sealed in a moisture barrier bag.

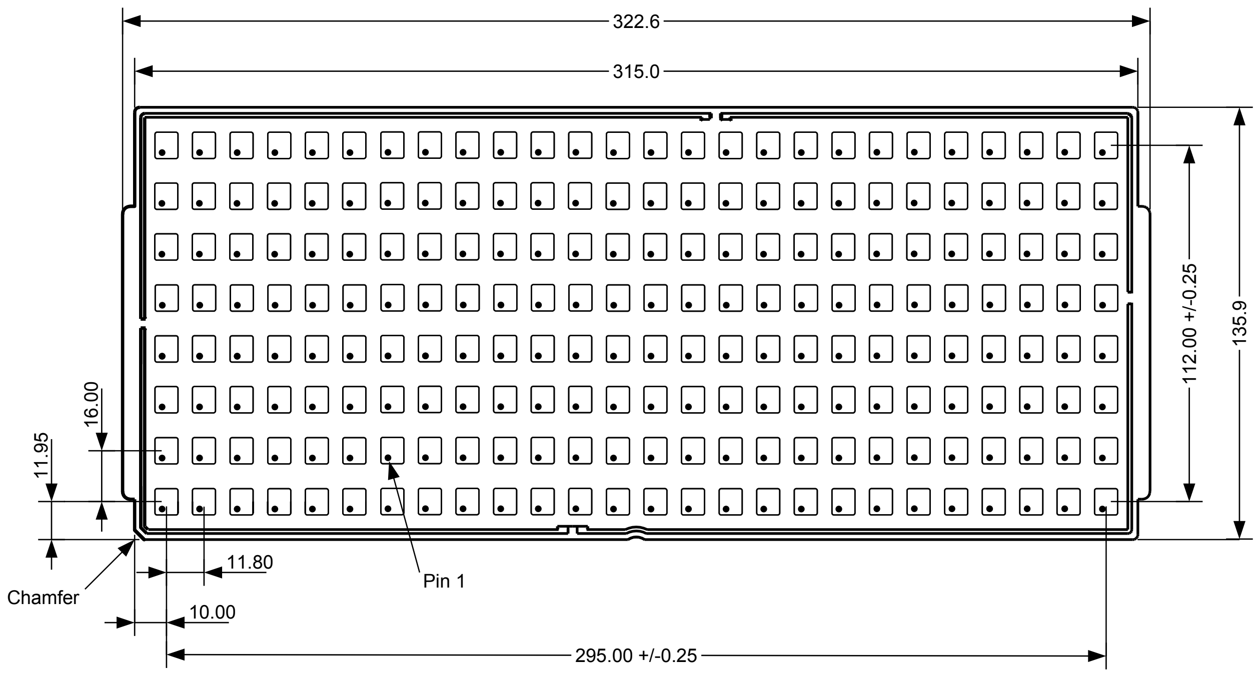


Figure 14: JEDEC tray for 26 x 8 pieces, maximum quantity 208 pieces per tray, use vacuum pick-up
(all measures in mm)

4. Ordering information

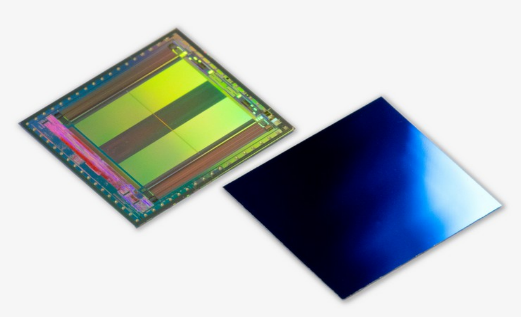


Figure 15: epc660-CSP68 bottom and top side

Figure 16: epc660 CC Chip Carrier, refer to separate datasheet

Part Number	Part Name	Package	RoHS compliance
P100 183	epc660-CSP68	CSP68	Yes
P100 244	epc660 CC Chip Carrier	PCB 37.25 x 36.00 mm	Yes

Table 10: Ordering Information

4.1. Notes to various chip releases

The supplied chip version can be identified by
- reading the extension -XXX of the part name on the packaging labels or delivery papers: epc660-CSP68-XXX.
- reading the part version register 0xFB: Refer to chapter 15.8.
- The latest download code for each chip version is included in the download package for the epc660 Evaluation Kit (see chapter 15.11).

5. Hardware implementation

5.1. Typical application diagram

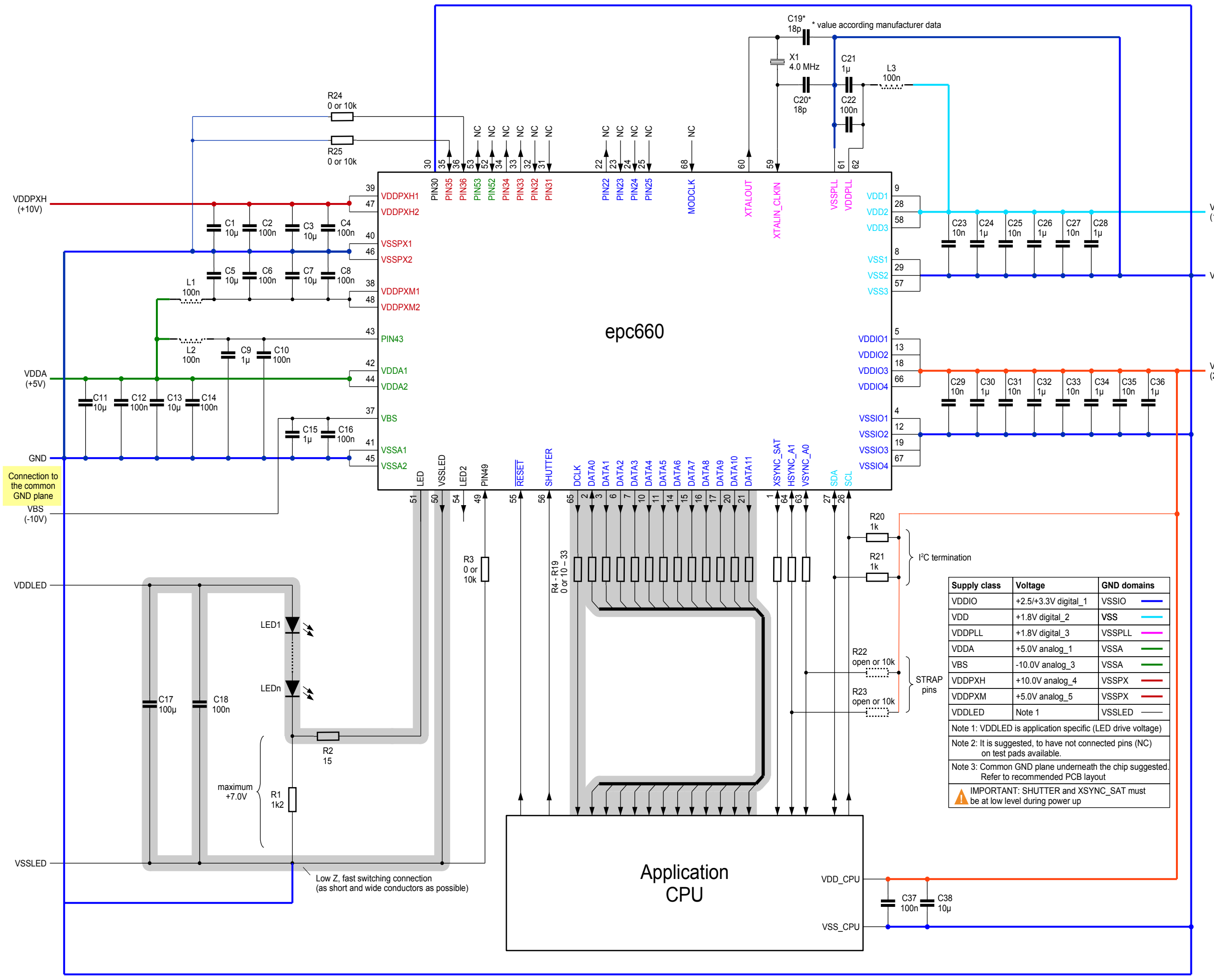


Figure 17: Typical application diagram

Notes:

R4-R19	Resistor value depends on fast bus decoupling, typically 33 Ohms.
R3, R24, R25	Pins need to be connected to GND. In case of need to testability: use 10k resistors.
R22, R23	Resistor value depends of needed strap function.
SHUTTER and XSYNC_SAT	Must be at low level until RESET release. Otherwise malfunction occurs.
VSS	Connect all VSS as direct as possible using vias to the GND plane underneath the imager

5.2. Application diagram part list

Part designator	Description	Pin No.	Value			Toler-ance	Supply class V_{SC}	Comments
			Min.	Typ.	Max.			
Minimum part count:								
C11	VDDA	41 – 42, (44 – 45)	10 µF			±20%	V_{DDA}	Ceramic X7R
C12	VDDA	41 – 42, (44 – 45)		100 nF		±20%	V_{DDA}	Ceramic X7R
C19, C20	XTAL	59 - 61, 60 - 61	---	18 pF [2]	---	±20%	V_{DDPLL}	Ceramic NPO
X1	XTAL	59 - 60	---	4 MHz	---	±100ppm	V_{DDPLL}	Quartz / Resonator
R20, R21	I²C pull-up			1 kOhm		±20%	V_{DDIO}	Resistors
Dashed components improve signal quality, power supply quality or testability:								
C1, C3	VDDPXH	46 – 47, 39 - 40	10 µF			±20%	V_{DDPXH}	Ceramic X7R
C5, C7	VDDPXM	46 – 48, 38 - 40	10 µF			±20%	V_{DDPXM}	Ceramic X7R
C13	VDDA	44 – 45	10 µF			±20%	V_{DDA}	Ceramic X7R
C9	PIN43	41 - 43	1 µF			±20%	V_{IR}	Ceramic X7R
C15	VBS	37 - 41	1 µF			±20%	V_{BS}	Ceramic X7R
C21	VDDPLL	61 - 62	1 µF			±20%	V_{DDPLL}	Ceramic X7R
C24, C26, C28	VDD	8 – 9, 28 – 29, 57 - 58	1 µF			±20%	V_{DD}	Ceramic X7R
C30, C32, C34, C36	VDDIO	4 – 5, 12 – 13, 18 – 19, 66 - 67	1 µF			±20%	V_{DDIO}	Ceramic X7R
C2, C4	VDDPXH	46 – 47, 39 - 40		100 nF		±20%	V_{DDPXH}	Ceramic X7R
C6, C8	VDDPXM	46 – 48, 38 - 40		100nF		±20%	V_{DDPXM}	Ceramic X7R
C10	PIN43	41 – 43		100 nF		±20%	V_{IR}	Ceramic X7R
C14	VDDA	44 – 45		100 nF		±20%	V_{DDA}	Ceramic X7R
C16	VBS	37 - 41		100 nF		±20%	V_{BS}	Ceramic X7R
C22	VDDPLL	61 - 62		100 nF		±20%	V_{DDPLL}	Ceramic X7R
C23, C25, C27	VDD	8 – 9, 28 – 29, 57 - 58		10 nF		±20%	V_{DD}	Ceramic X7R
C29, C31, C33, C35	VDDIO	4 – 5, 12 – 13, 18 – 19, 66 - 67		10 nF		±20%	V_{DDIO}	Ceramic X7R
L1	VDDPXM	---		100 nH		±20%	V_{DDPXM}	Inductor
L2	PIN43	---		100 nH		±20%	V_{IR}	Inductor
L3	VDDPLL	---		100 nH		±20%	V_{DDPLL}	Inductor
R4 - R19	Bus termination		0 Ohm	10 Ohm	33 Ohm	±20%	V_{DDIO}	Resistors
R22, R23	I²C address			10 kOhm		±20%	V_{DDIO}	Resistors

Table 11: Values of component related to epc660 chip, see Figure 17

Notes:

[1] All other components are application specific.

[2] The capacitor value has to be selected according the crystal or resonator supplier's recommendation.

5.3. Hardware implementation notes

1. epc660 is supplied with +1.8V, +2.5/3.3V, +5V, +10V and -10V. See Figure 17.
2. Decoupling capacitors must be placed as close as possible to their supply pin pair in order to minimize ripple on the supply rails due to fast switching high-speed signals (Table 11).
3. +1.8V is used for supplying the digital logic (VDD), the on-chip oscillator OSC and the phase-look-loop PLL (VDDPLL). These supplies are marked in the application diagram as VDD and VDDPLL respectively (Figure 17). Their supply wiring must be separated from the digital wires and physically isolated from each other. The XTAL/OSC and PLL are critical parts of the chip which directly impacts the optical system performance (i.e. distance calculation). Thereof, the VDDPLL supply needs a well decoupling from VDD, because the digital logic creates some internal switching noise on VDD.
4. +2.5/3.3V (VDDIO) is used for supplying the high-speed IO pins (MODCLK, TCMI and LED2) and the slow I²C pins. High speed TCIM pins toggle up to 48MHz during data transfer, hence generating continuously switching noise (much more dominant than the digital noise). Therefore, VDDIO supply wires and layers must be carefully designed and isolated in a separate supply island on the PCB. It is not recommend to change this voltage on the fly when the TCMI, LED2 or I²C interfaces are running. When the application needs power saving during system idle periods, it can be scaled from +3.3V down to +2.5V, only after frame acquisition is stopped and both interfaces are completely inactivated. It can be increased back to +3.3V before re-activating the chip for frame acquisition, accessing

I^{2}C, LED2 or TCMI interface. Note that voltage scaling must be done in a controlled way having both application CPU's and epc660's IO voltages at the same time at the same level.

5. +5V is used for supplying analog blocks of the chip e.g. pixel-field drivers and ADC readout circuitry. Refer to Figure 17.
6. +10V (VDDPXH) is used for supplying the pixel-field circuitry.
7. -10V (VBS) is used for biasing the the pixel-field like reverse-biasing a photodiode. The use of a stable supply source with a low ripple is recommended. There is no switching or active internal circuit dependent current consumption, except ambient-light dependent leakage current (refer to Table 1, note 8).
8. A 4MHz quartz crystal or a ceramic resonator is connected to XTALIN_CLKIN and XTALOUT pins in order to use internal oscillator OSC as time base for the epc660. The frequency accuracy and stability are directly related to the distance readings. Alternatively an external clock source can be used (chapter 5.4).
9. MODCLK input can be used for user controlled/modulated clock. It is used for both the LED driver and the pixel-field demodulator.
10. SCL, SDA are I^{2}C slave pins which need external pull-up resistors on the PCB (see also VDDIO supply). Values of R20 and R21 are given only for indicative purpose and must be re-calculated according to the total capacitive load of all I^{2}C slave/master devices and the operating mode FM or FM+ of the I^{2}C (chapter 13) in the application.
11. VSYNC_A0, HSYNC_A1, XSYNC_SAT, DATA[11:0], DCLK, high-speed TCMI signals (chapter 6), SHUTTER and $\overline{\text{RESET}}$ control signals toggle in the VDDIO range. To minimize the skew, the high-speed *SYNC, DATA[11:0], DCLK signals wires must be routed equal in impedance and length less than 10cm long with less than 10mm difference on the PCB. As they are toggling all the time, they can be separated with ground wires on the side adjacent to other signals/supply lines, routed with enough distance from other sensitive signal wires on the board. Series termination resistors R4 … R19 (10 … 33Ω) are needed at high-speed outputs to control the slew.
12. Optional pull-up resistors R22 and R23 (10kΩ) set initial values of some configuration registers during start up of the chip. Such outputs pins are called strap pins. They are scanned one time immediately after $\overline{\text{RESET}}$ is released (chapter 5.6.3).
13. The LED pin is an open-drain LED/LD driver output. When the driver is active (on), the LED/LD on-current flows through the power resistor R2 into the LED pin, through the driver and comes out of the chip on the VSSLED ground pin. The LED pin toggles up to 24MHz or according to the MODCLK clock with a current maximum of 200mA limited by the resistor R2. The number of IR LEDs depends on the level of the LED supply voltage and the turned-on forward voltage drop of the IR LEDs. This signal creates a lot of ground noise. Therefore, VSSLED pin is decoupled from the other analog grounds internally. It must be shorted with the other analog ground pins with a low-ohmic connection as short as possible on the PCB. In this way, there will be minimal voltage differences in the ground planes of the board. The LED supply line must be isolated properly from any analog supply on the PCB to minimize noise coupling from the LED drivers.

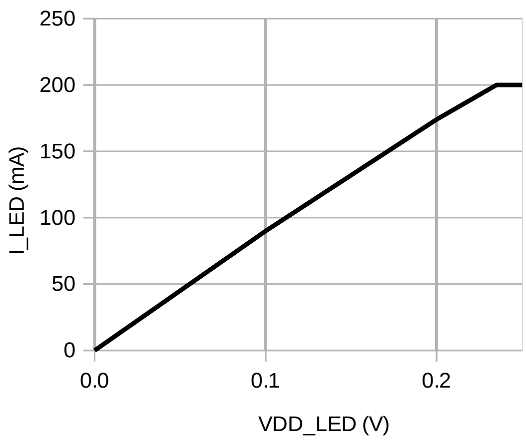


Figure 18: Output characteristic I_{LED} versus V_{DDLED}.
Refer for maximum values of V_{DDLED} and I_{LED} to Table 1 and Table 2

14. The LED2 pin is the alternative push-pull driver providing symmetric rise/fall times to drive external LED driver. It works from the +2.5/+3.3 VDDIO supply (VSSIO GND domain) and swings in the same voltage range like the TCMI pins. LED2 = LOW (approx. 0V) corresponds to LED = OFF (max. output voltage). LED and LED2 pins must not be used at the same time for driving the external illumination. They exhibit different phase delays and this can result wrong distance measurements. None of the TCMI pads toggle during integration time, LED2 pin is the only toggling during integration time and it is not affected from switching noise of others.
15. It is recommended having “not connected pins” (PINxx) on test pads available. It helps e.g. to check after assembly for correct orientation of the chip or for short-cuts.
16. Pins not listed here have to be connected according Figure 17.

5.4. Clock source

Instead of a crystal, an external 4MHz clock source can be connected to the XTALIN_CLKIN pin. XTALOUT output pin left unconnected. Input clock signal levels must match VDDPLL/VSSPLL supply levels (Table 1). If the external clock source comes from the +2.5/3.3V voltage domain, a resistor divider circuit can be deployed to adjust the voltage level according to Figure 19.

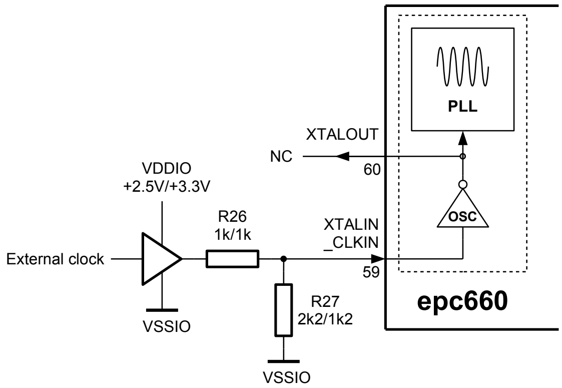


Figure 19: Resistor divider to adjust external clock voltage levels to XTALIN_CLKIN

IMPORTANT: The optical performance of the chip directly depends on the input clock precision/stability. XTALOUT must not be used to drive external loads.

5.5. External modulation MODCLK

The epc660 has for enhanced user applications the possibility to bring an external modulation clock to the chip. The optional MODCLK input can be used to inject a user controlled/modulated clock for both the LED driver and the pixel demodulator, see Figure 20.

The external MODCLK can be used e.g. in concepts for reliable multi camera applications. It allows to use e.g. frequency-division multiple access (FDMA). In corresponding literature, the details of these concepts are explained in detail.

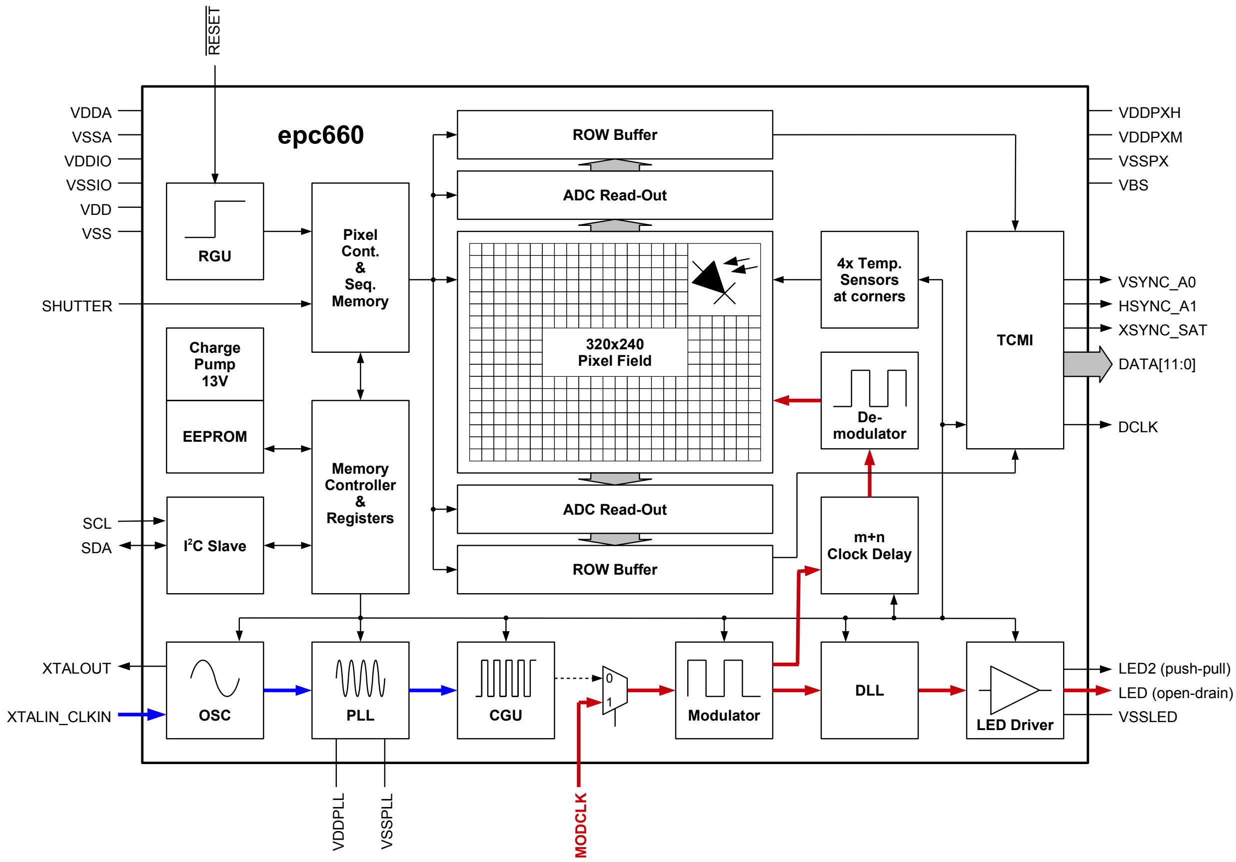


Figure 20: The MODCLK signal flow (red marked)

The user is free to apply any digital waveform up to 96MHz during frame acquisition as external MODCLK signal. Even more, he is also free to use modulations like pseudo-random edge jitter, dithering, etc.

The signal from the MODCLK pin is used instead of the clock generated by the CGU if bit 6 in register 0x80 is set to 1. The effective modulation signal is the MODCLK divided by 4.

The unambiguity range and the integration time are in this case based on the MODCLK:

[1] $$t_{INT} = \frac{reg(0x85) + 1}{MODCLK} \cdot [reg(0xA2:0xA3) + 1] \cdot reg(0xA0:0xA1)$$

For more details refer to chapter 9.2.1 and 11.4. Note, register 0x85 is active in this mode.

5.6. Supply, reset and start-up options

5.6.1. Supply voltages and external reset

During the power-up sequence, VDD and VDDPLL supplies (Figure 21) must be applied at the same time to the epc660. VDDIO can be applied either at the same time or after VDD and VDDPLL supplies become stable. In a system where VDDIO voltage is connected in parallel to application CPU IO supply pins (see Figure 17), VDD and VDDPLL can be generated by a linear regulator directly from VDDIO supply. In this case, all these three supplies ramp together.

VDDA, VDDPXM and VDDPXH supplies must be applied as a second group, after all VDD, VDDPLL and VDDIO supplies become stable.

The negative supply VBS must be applied after all positive supplies reached their rated levels.

Image acquisition shall not start before all supply voltage are at their stable level.

$\overline{\text{RESET}}$ must be kept low while all positive voltages are ramping-up in order to guarantee proper reset of all internal circuits. As soon as rated positive levels are reached, $\overline{\text{RESET}}$ can be set to high. In case of an external clock is applied at XTALIN_CLKIN instead of a crystal/resonator is used with on-chip OSC, clock must be present before $\overline{\text{RESET}}$ is released.

IMPORTANT:

- It is possible to shutdown entire supplies for a very low standby current. In that case, first $\overline{\text{RESET}}$ must be driven low, then supplies must be turned off in the reverse order. Refer for details to chapter 11.5
- VDDA, VDDPXM and VDDPXH supplies must never kept on while turning off VDD, VDDPLL and VDDIO. Damage to the chip can be the result.

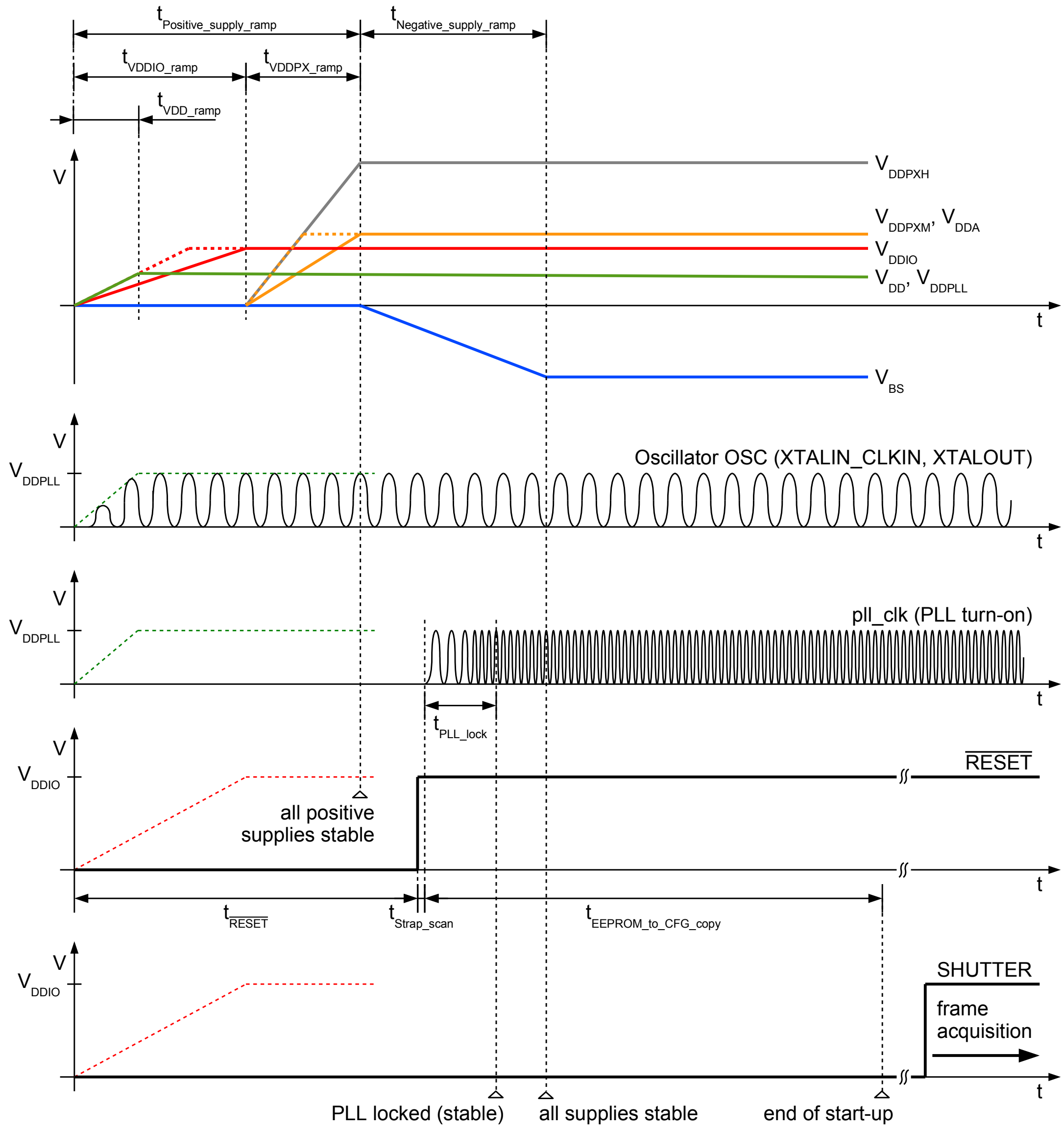


Figure 21: Power-up and reset sequence

5.6.2. Start-up (Clock, PLL turn-on and EEPROM copy)

The epc660 starts using either the internal 4MHz oscillator OSC with a crystal/resonator (Figure 17) or an external 4MHz clock, followed by an EEPROM copy sequence in parallel to the PLL turn-on phase. This is the factory default configuration. Several configuration registers are modified by copying the EEPROM content (Figure 58, i.e. overwrite reset values).

5.6.3. Strap pins

The epc660 has output pins with dual/alternative functionality for PCB level flexible start-up configuration changing, called 'strap pins'. $\overline{\text{RESET}}$ release is followed by a strap pin scanning step. The chip programs its strap pins as inputs with internal pull-down resistors enabled for 4 osc_clk periods (refer to Table 1 and Table 3.). If there is no external pull-up resistor connected, the corresponding strap pin will be scanned as logic 0 due to the internal pull-down resistor. If there is an external pull-up resistor connected (Figure 17), it will override the internal pull-down and corresponding pin will be scanned as logic 1. After the strap scan period, pins are programmed back as outputs so that they can be used for their main function. Strap pins and their definitions are listed below (Table 12).

Pin	Pin no.	Definition
HSYNC_A1	64	Set A1 bit of 7-bit I²C slave device address (section 13.1).
VSYNC_A0	63	Set A0 bit of 7-bit I²C slave device address (section 13.1).
XSYNC, DATA0	1, 2	Factory used strap pins. No pull-up resistors allowed

Table 12: Strap pin definition

5.7. LED driver

The LED driver register 0x90 is used for setting polarity etc. depending on the external LED/LD circuitry used in the application. These bit fields must not be modified during frame acquisition.

IMPORTANT: There are non-modulating DC modes (e.g. grayscale with LED/LD illumination) which keeps the LED driver always turned on. In this case, the user has to take care that LED driver and the epc660 chip does not exceed the maximum operating limits.

5.8. DLL (Delay Line)

The modulation signal can intentionally be delayed in order to add a phase shift between the modulation of the light source and the demodulation of the backscattered light, refer to Figure 22.

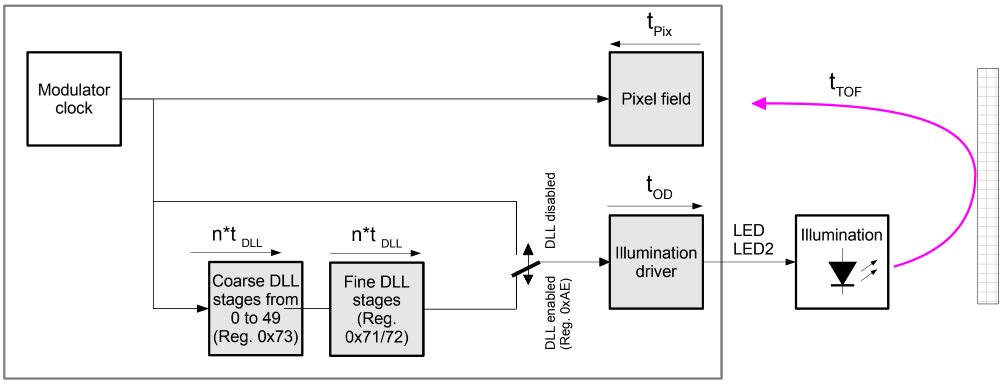


Figure 22: Block diagram of the DLL function

The purpose to do so can be that the phase shift between the modulated and the demodulated signal in a specific distance range should be at a certain value. For example, the highest distance accuracy with lowest distance noise can be achieved when the phase angle of demodulation is 45°. This is the case when all four DCS amplitudes have the same or a similar value. The worst situation is if one DCS pair is at its maximal amplitude whereas the other DCS pair is around zero (refer to Figure 23).

The DLL can be enabled in register 0xAE whereas the delay of the LED modulation can be set in steps t_{DLL} by register 0x73 (approx. 2ns/step). The exact step t_{DLL} by can be calculated with the value and the formula listed in register 0xE9. This value is varying from chip to chip and is also temperature dependent. The user shall characterize the overall temperature drift of the complete camera for matching the compensation.

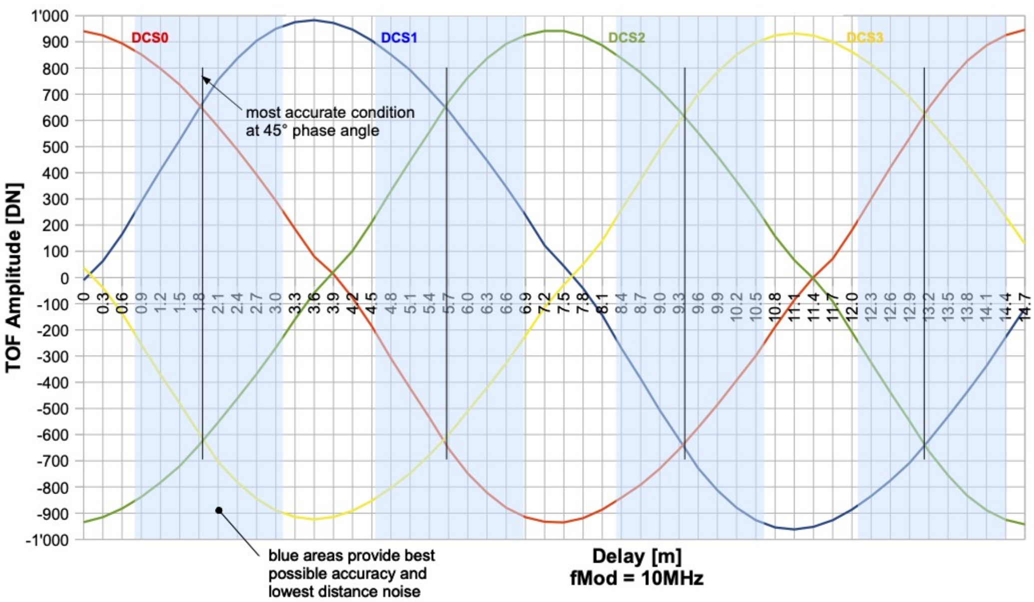


Figure 23: DCS amplitudes for the 4 DCSx (measurement data)

Example for 10MHz modulation frequency:
If we want to optimize the accuracy of our TOF camera in the short range domain, e.g. 0m to 1m, the situation shown in Figure 23 is not ideal at all. The modulation frequency of the data shown in Figure 23 is 10MHz whereas 50 DLL Steps of approx. 2ns are equivalent to 15m distance. Shown in the diagram, the worst condition is in the first three DLL steps, which is equal to 0m to 0.9m. From then on, the distance accuracy becomes much better until DLL step 12. In other words, the distance accuracy from distance 0.9m to 3.0m is very good, but not from 0m to 0.9m. In order to be in an accurate distance measurement regime, the DLL should be shifted by 3 steps which means that the LED is delayed by 6ns.

5.9. Application system overview

Figure 24 and Figure 25 show a typical application block and data flow diagram. The epc660 chip acquires image data, controlled via the I²C interface, and then submits the data via the TCMI to an FPGA or microcontroller. The FPGA or microcontroller calculates the distance from the DCS and does filtering, correction and compensation and provides a cleaned "point cloud" to the host system.

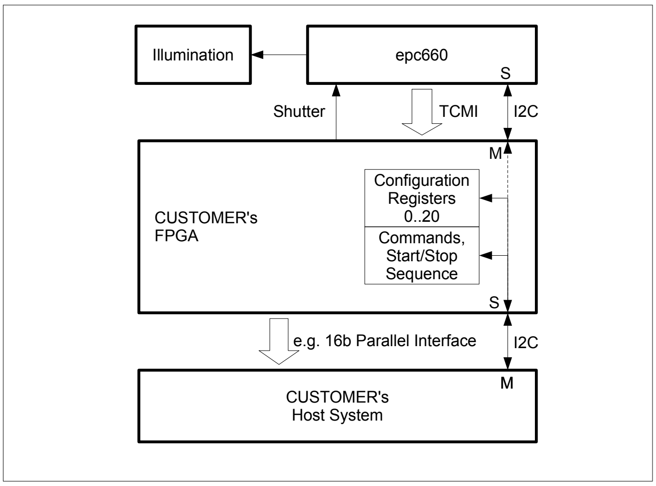


Figure 24: Block diagram

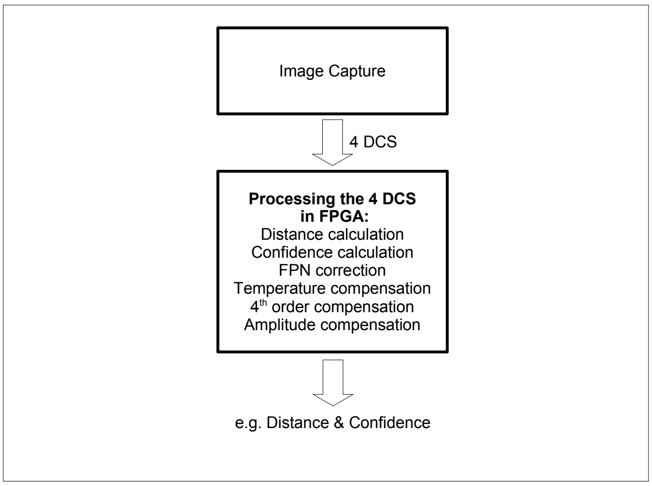


Figure 25: Data flow

6. TOF camera interface (TCMI)

The TOF Camera Module Interface (TCMI) is a programmable high-speed parallel data output interface to down-load the pixel data. It can be programmed very flexible via the registers 0x89, 0xCB and 0xCC.

When the integration period is completed and ADC conversion is finished, the readout results are moved into the data out buffers to be immediately transmitted via the TCMI interface. The ADC conversion is two full rows in parallel (top and bottom pixel-field) and the conversion time is independent of the number of selected columns. Depending of the mode selection (4x DCS, 2x DCS, ...) a programmable number of DCS frames are generated. The data is streamed out as a complete block of 1 DCS frame, one after the other. Each row contains 12-bit DCS values and the SAT bit. The pixel values are streamed out as 12 bit signed numbers. Two rows are streamed out in sequence together, the first one from the top and the second one from the bottom pixel-field e.g. R125 (C4, C5, … C323), R126 (C4, C5, … C323), R124 (C4, C5, … C323), R127 (C4, C5, … C323) and so on until R6 (C4, C5, … C323), R245 (C4, C5, … C323). The stream-out of a row pair takes 26.7µs with default clock settings (24MHz TCMI clock rate).

The transfer of a DCS frame cannot be interrupted or stopped, once it is started. The application should have enough bandwidth to receive all transmitted frames.

IMPORTANT: Refer to register 0xCC for setting correct data format.

6.1. TCMI clock

The TCMI interface supports the continuous clock mode with DCLK signal toggling continuously. It transmits the frames at high-speed using all *SYNC (VSYNC_A0, HSYNC_A1, XSYNC_SAT), DATA[11:0] and DCLK outputs (Figure 26). The DCLK frequency is programmable to 12, 24, 48 MHz via register 0x89.

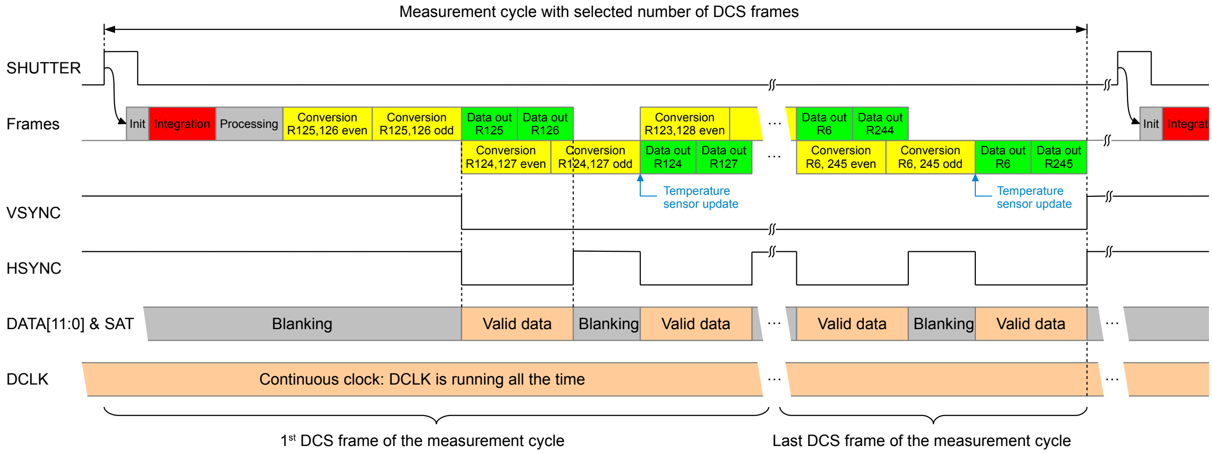


Figure 26: Continuous clock mode

All *SYNC*, DATA[11:0] signals are synchronously updated with the positive edge of the DCLK signal when its polarity is set as active-high; with the negative edge of the DCLK signal when its polarity is set as active-low. The non-active edge of the DCLK output can be used by the receiving end (application CPU) as a sampling clock. It should approximately be in the center of the data (refer to Figure 28). By using the default configuration, the active states of VSYNC_A0 and HSYNC_A1 signals indicate blanking periods during the frame transmission. While DCLK toggles continuously, any data during the blanking periods are not valid and must be ignored.
As soon as the measurement result of the first row of the new frame is available, VSYNC_A0 and HSYNC_A1 are set consecutively with the next active edge of DCLK. VSYNC_A0 is active from the start until the end of the each complete frame. Whereas, HSYNC_A1 indicates the validity of the DATA[11:0] and XSYNC_SAT (saturation bit) from the start until the end of a row pair.
By default, the XSYNC_SAT pin is used for the saturation bit. Optionally, it can be programmed to indicate the end of a frame by disabling bit 6 in register 0xCC.

6.2. Single or continuous measurement control

6.2.1. Single measurement control

The selected measurement mode (4x DCS, 2x DCS, grayscale, …) defines, how many frames the chip performs by the stimulation of one SHUTTER pulse for a measurement cycle. This pulse can be applied either by the HW SHUTTER pin or by SW control with bit 0 in register 0xA4. Whereas the SW controlled SHUTTER is auto-cleared after propagation, the HW Shutter needs a minimum hold time of 250ns and must be set back manually latest before the HSYNC_A1 signal of the last row pair of the last DCS frame (last HSYNC_A1 of the last frame). During such a measurement cycle, the next frame acquisition starts immediately after the last data readout on the TCMI interface until all frames are performed.

6.2.2. Continuous measurement control (auto-run)

As long as in the shutter control register 0xA4, bit 1 is set or the HW SHUTTER is applied during the readout of the last row pair of the last frame, the epc660 runs in a non-stop measurement mode. The chip starts immediately next measurement cycle if the actual one is terminated (Figure 30). Trigger signals not active during the readout of the last row pair of the last frame are ignored.

6.3. TCMI timing

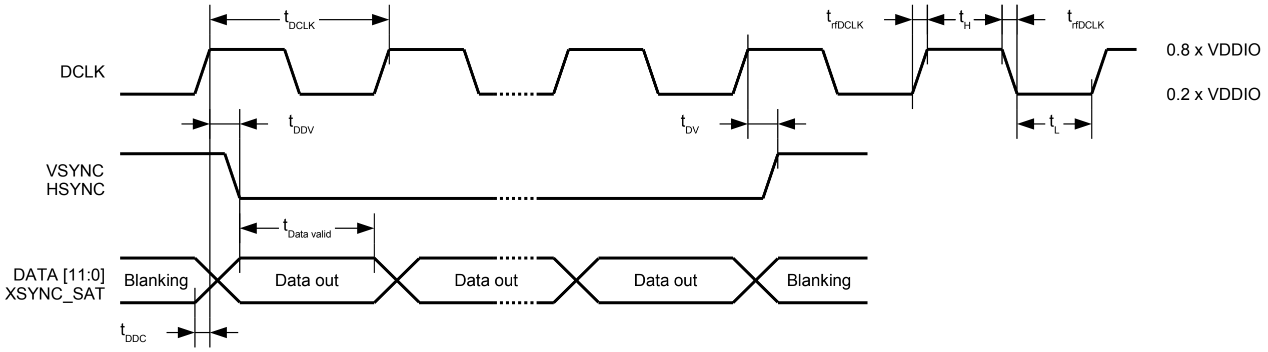
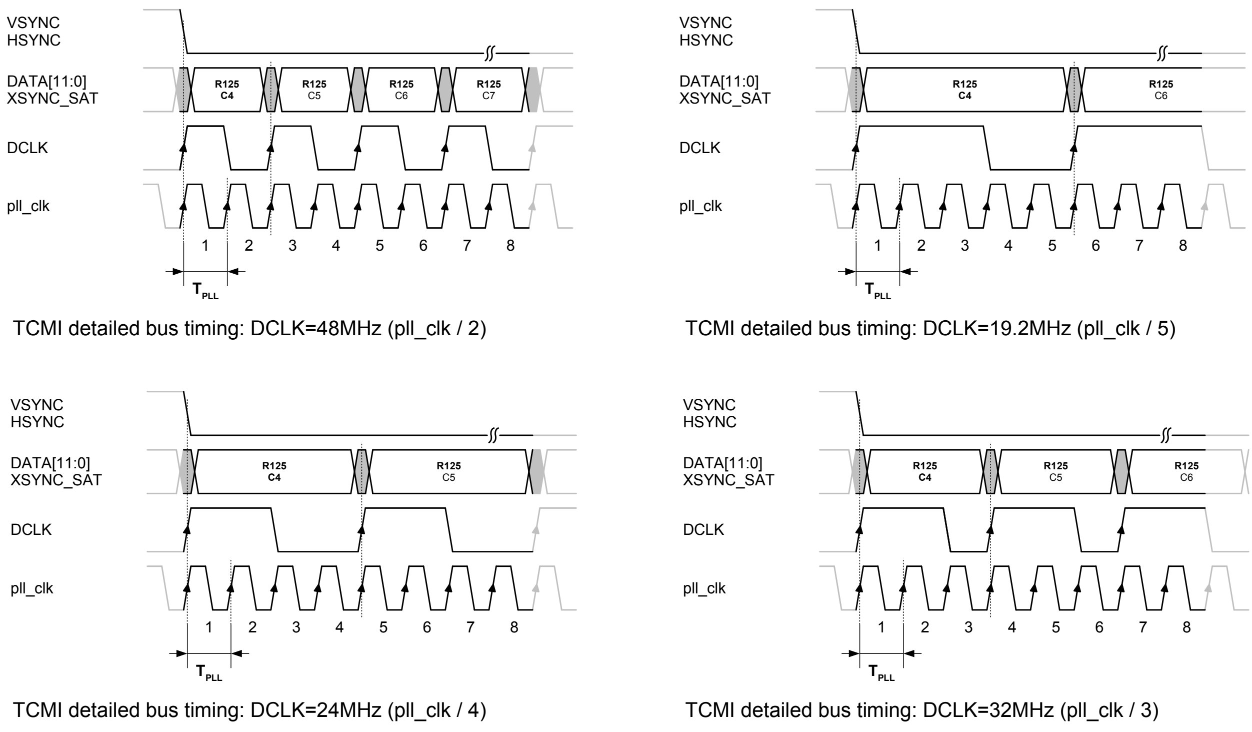


Figure 27: Detailed TCMI timing

Symbol	Parameter	Min.	Typ.	Max.	Units
t_{DCLK}	TCMI readout clock: typ. f_{DCLK} = 24MHz / max. f_{DCLK} = 48MHz		41.6	20.8	ns
t_{DDV}	Delay time after positive edge of DCLK until data are valid			2.0	ns
t_{DDC}	Data start changing before positive edge of DCLK			1.7	ns
t_{rfDCLK}	Rise and fall time of DCLK, VSYNC, HSYNC, XSYNC, Data[11:0]			2.0	ns
t_H	High period of DCLK	5.0			ns
t_L	Low period of DCLK	3.5			ns
$t_{Data\ valid}$	Output data on the TCMI interface are valid (depends on DCLK)	8.8			ns

Table 13: TCMI timing parameters (C_L = 20 pF max.)



TCMI detailed bus timing: DCLK=48MHz (pll_clk / 2)

TCMI detailed bus timing: DCLK=19.2MHz (pll_clk / 5)

TCMI detailed bus timing: DCLK=24MHz (pll_clk / 4)

TCMI detailed bus timing: DCLK=32MHz (pll_clk / 3)

Figure 28: TCMI timing examples with symmetric and asymmetric DCLK

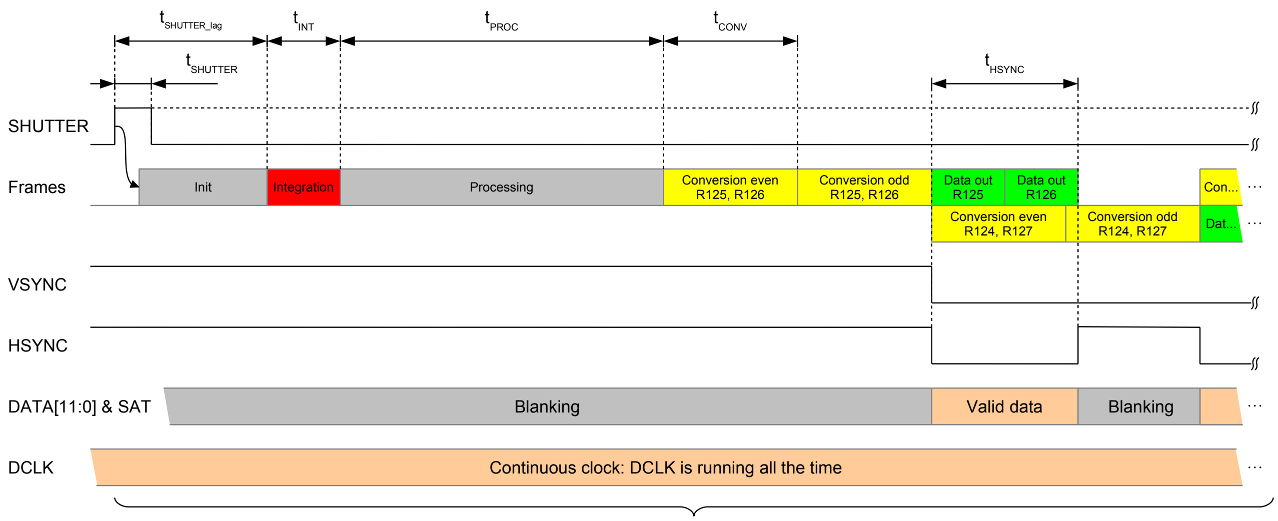


Figure 29: Frame timing: Start 1st DCS frame

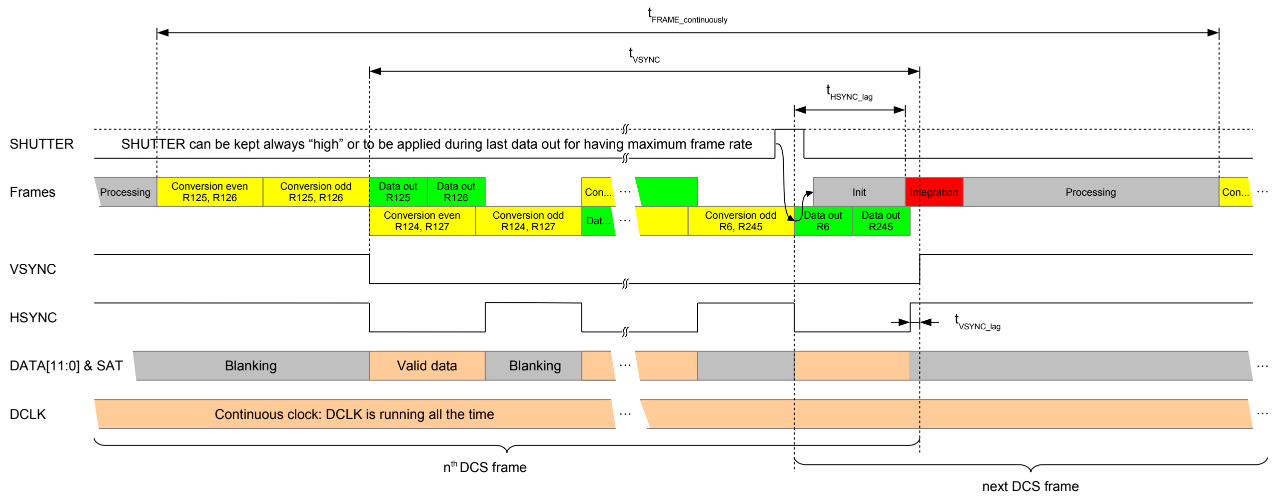


Figure 30: Frame timing: Inter frame timing, end of frame and start next frame

Note:
To avoid readout rollover when using slower DCLK with default ROI (< 13MHz, register 0x89 > 0x06), register 0x91, bit 6 must be enabled. It stretches HSYNC for slower TCMI interfaces. It causes a reduced DCS frame rate due to additional 2µs per ADC conversion (t_{conv} + 2µs).

6.4. TCMI data format

TCMI supports one 12 bit and three 8 bit transfer formats:

- 12-bit mode: Transfers 12 bit pixel data with 1x DCLK (default). Refer to Figure 31.
- msb/lsb split mode: Transfers 12 bit pixel data with MSByte leading and LSByte trailing with 2x DCLK. Refer to Table 14 and Figure 32.
- lsb/msb split mode: Transfers 12 bit pixel data with LSByte leading and MSByte trailing with 2x DCLK. Refer to Table 15 and Figure 33.
- 8-bit mode: Transfers the 8 MSB bits of the pixel data with 1x DCLK. Refer to Table 16 and Figure 35.

12-bit mode uses all lines DATA[11:0]. Whereas the three 8-bit modes require only lines DATA[7:0] to be connected in the application. The TCMI data format can be selected in the register 0xCB.

The two split modes transmit pixel values in two consecutive DCLK cycles. As a result HSYNC time is doubled. When 8 bit precision is enough, the application can use 8-bit mode.

1st Byte: MSByte								2nd Byte: LSByte							
D7	D6	D5	D4	D3	D2	D1	D0	D7	D6	D5	D4	D3	D2	D1	D0
SAT	0	0	0	b11	b10	b9	b8	b7	b6	b5	b4	b3	b2	b1	b0

Table 14: TCMI msb/lsb split mode

1st Byte: LSByte								2nd Byte: MSByte							
D7	D6	D5	D4	D3	D2	D1	D0	D7	D6	D5	D4	D3	D2	D1	D0
b7	b6	b5	b4	b3	b2	b1	b0	SAT	0	0	0	b11	b10	b9	b8

Table 15: TCMI lsb/msb split mode

Byte							
D7	D6	D5	D4	D3	D2	D1	D0
b11	b10	b9	b8	b7	b6	b5	b4

Table 16: TCMI 8-bit mode , HW synchronization data format

The saturation flag can be optionally inserted into the DATA[7] of the MSByte by setting bit 6 in register 0xCB during the first or second DCLK cycle for the msb/lsb or lsb/msb split modes, respectively. This feature is not available for the 12-bit and 8-bit mode. In this cases either the XSYNC_SAT pin can be used along with the DATA[*] pins or bit 7 in register 0xCC must be set to force all DATA[*] = 0xFFF when the corresponding pixel is saturated.

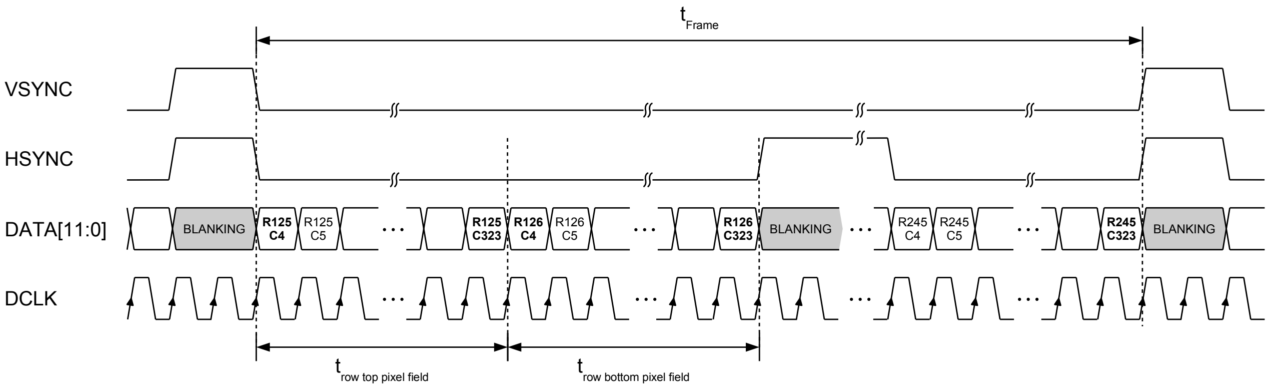


Figure 31: 12-bit mode data readout

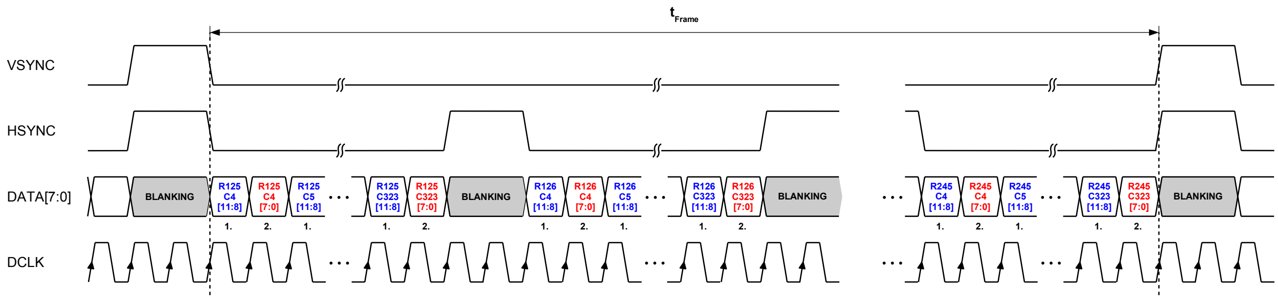


Figure 32: msb/lsb split mode

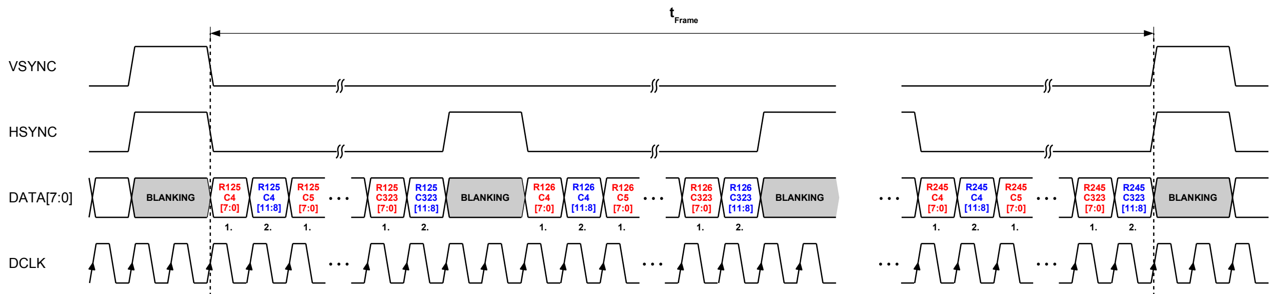


Figure 33: lsb/msb split mode

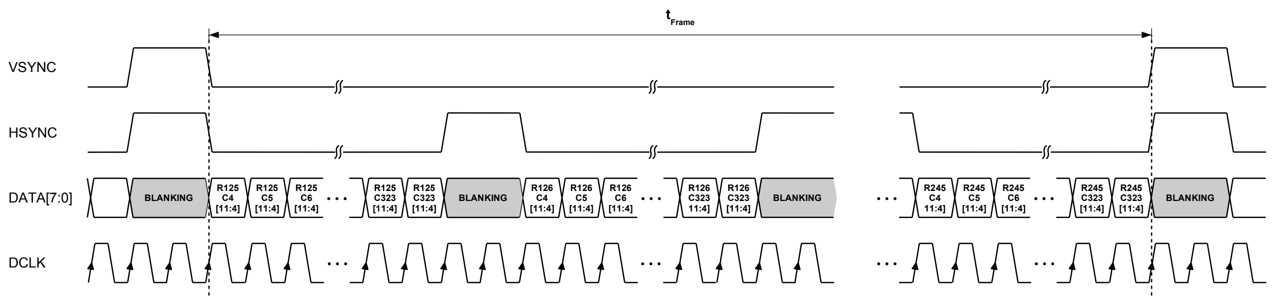


Figure 34: 8-bit mode

6.5. Frame rate and data-out performance

6.5.1. Frame rate QVGA 320x240 pixel (default)

The epc660 can perform a maximum of 158 fps with 1µs integration time, 12MHz modulation clock, 48MHz DCLK, 1x DCS and continuous measurement control. For 3D TOF, each frame is referred as a DCS frame. Either 4x (with π-delay matching) or 2x (without π-delay matching) DCS frames must be acquired for one distance calculation. Therefore, the resulting distance measurement rate turns out to be 39 fps or 79 fps respectively. For the grayscale mode the maximum frame rate of 158 fps is possible.

Symbol	Parameter	Min.	Typ.	Max.	Units
t_{DCLK}	TCMI readout clock e.g. f_{DCLK} = 48MHz		20.8		ns
$t_{SHUTTER}$	Hold time for the signal on pin SHUTTER	250			ns
$t_{SHUTTER\_lag}$	Delay from the rising edge of SHUTTER signal to the 1st LED pulse		18		µs
t_{INT}	Image acquisition (integration time)		1		µs
t_{PROC}	Delay from the last LED pulse until the 1st row conversion		38.75		µs
t_{CONV}	Conversion time for a pair of half rows (even or odd)		26.042		µs
t_{HSYNC}	Readout time for a pair of rows e.g. f_{DCLK} = 48MHz		13.33		µs
t_{HSYNC_lag}	Delay from the begin of last readout until the 1st LED pulse of next DCS frame		17		µs
t_{VSYNC_lag}	Delay end of HSYNC to end of VSYNC at the end of each DCS frame		50		ns
t_{VSYNC}	Data readout time for one DCS frame e.g. f_{DCLK} = 48MHz $t_{VSYNC} = (2x\ t_{CONV}\ x\ 119\ rows) + t_{HSYNC} + t_{VSYNC\_lag}$		6'261		µs
	Single measurement control mode:				
$t_{1st\_FRAME\_START}$	Delay from rising edge of SHUTTER signal until start of data readout of 1st frame		83.79		µs
$t_{1st\_FRAME\_TOTAL}$	Total time for reading one DCS or grayscale frame from rising edge of SHUTTER signal until end of readout of 1st frame		6'345		µs
	Continuous measurement control mode:				
$t_{FRAME\_continuously}$	Total time for reading one DCS or grayscale frame $t_{FRAME\_continuously} = (2x\ t_{CONV}\ x\ 120\ rows) + t_{HSYNC\_lag} + t_{INT} + t_{PROC}$		6'307		µs
$t_{4DCS\_continuously}$	Total time for one 3D TOF distance measurement (4 DCS) $t_{FRAME\_continuously} = ((2x\ t_{CONV}\ x\ 120\ rows) + t_{HSYNC\_lag} + t_{INT} + t_{PROC}\ )\ x\ 4\ DCS$		25.23		ms

Table 17: Timings for one DCS or grayscale frames and for 3D TOF distance measurements (4x DCS)
(Reference: see Figure 29 and Figure 30, f_{DCLK} = 48MHz, t_{INT} = 1µs)

Ref.	Imager settings (Input)			Imager output		
Figure	Pixel-field mode	Binning hor., ver., both	Row reduction y-axis: 2, 4, 8	Resolution x-y [imager pixel]	DCS Frame rate [fps]	Frame size [3] [kbytes]
42	full resolution	no	1	320 x 240	158	150
42	full resolution	no	2	320 x 120	314	75
42	full resolution	no	4	320 x 60	617	38
42	full resolution	no	8	320 x 30	1'119	19
43	full resolution	horizontal	1	160 x 240	314	75
43	full resolution	horizontal	2	160 x 120	617	38
43	full resolution	horizontal	4	160 x 60	1'119	19
43	full resolution	horizontal	8	160 x 30	2'235	10
44	full resolution	vertical	2	320 x 120	314	75
44	full resolution	vertical	4	320 x 60	617	38
44	full resolution	vertical	8	320 x 30	1'119	19
45	full resolution	both	2	160 x 120	617	38
45	full resolution	both	4	160 x 60	1'119	19
45	full resolution	both	8	160 x 30	2'235	10
46	dual modes [1]	no [2]	1	2 x 320 x 120	158	150
46	dual modes [1]	no [2]	2	2 x 320 x 60	314	75
46	dual modes [1]	no [2]	4	2 x 320 x 30	617	38

Table 18: Frame rate and resolution for default ROI setting 320 x 120 pixel, top-left (4, 6) and bottom-right (323, 125)

Notes:
[1] Frame rate and frame size are identical for dual phase and dual integration time mode (dual modes).
[2] Binning cannot be used with dual phase and dual integration time mode.
[3] Frame size is based on 2 Bytes per pixel to store in the application frame buffer.

6.5.2. Frame rate Half QQVGA 160x60 pixel

This example shows the ROI set symmetrically to 2 x 160 x 30 (Half-QQVGA) in the middle of the pixel-field: epc635 emulation. The frame time scales linearly with the reduced number of rows readout (see Table 19). The TCMI data-out time scales linearly with the reduced number of columns set in the ROI.

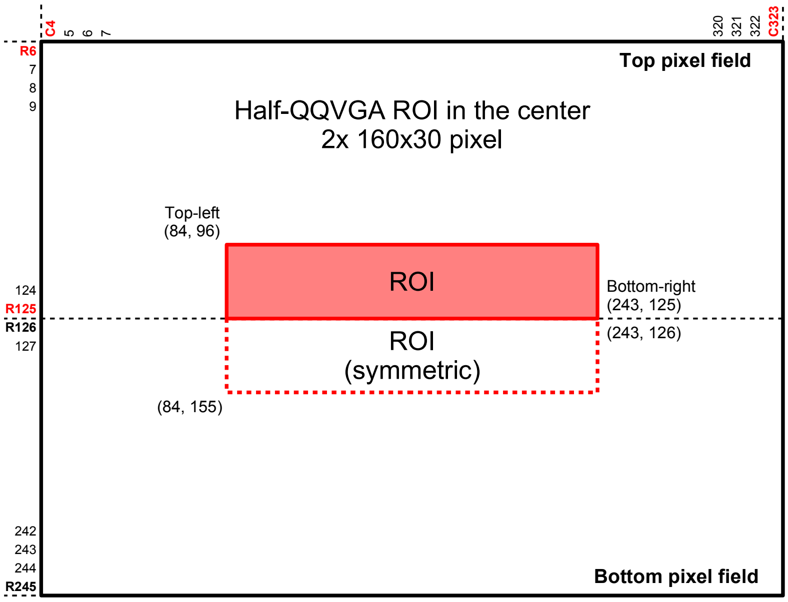


Figure 35: ROI for Half-QQVGA: 2 x 160 x 30 pixel

Ref.	Imager settings (Input)			Imager output		
Figure	Pixel-field mode	Binning hor., ver., both	Row reduction y-axis: 2, 4, 8	Resolution x-y [imager pixel]	DCS Frame rate [fps]	Frame size [2] [kbytes]
42	full resolution	no	1	160 x 60	617	19
42	full resolution	no	2	160 x 30	1'119	10
43	full resolution	horizontal	1	80 x 60	1'119	10
43	full resolution	horizontal	2	80 x 30	2'235	5
44	full resolution	vertical	2	160 x 30	1'119	10
45	full resolution	both	2	80 x 30	2'235	5
46	dual modes [1]	no [1]	1	2 x 160 x 30	617	19

Table 19: Frame rate and resolution for ROI setting: 160 x 30 pixel: top-left (84, 96) and bottom-right (243, 125)

Notes:
[1] Binning cannot be used with dual phase and dual integration time mode.
[2] Frame size is based on 2 Bytes per pixel to store in the application frame buffer.

6.5.3. Memory space estimation QVGA

Every frame (DCS) generates up to 320 x 240 pixel x 13 bit (Data + SAT) = 999 kBit. Stuffed to 16 bit words, the memory needed to store one DCS frame is 154kByte. Depending on the operation mode, up to 10 full frames or even more are needed. Thus, the minimum image memory RAM should be 1.5 MByte.

7. Pixel-field and architecture

The pixels are placed in groups 2x2 pixels, called herein "pixel group". The pixel group performs two basic operations: Measurement (integration) and readout (ADC). Pixels are named as UE (Upper-row, Even-column), UO (Upper-row, Odd-column), LE (Lower-row, Even-column) and LO (Lower-row, Odd-column) depending on their location within the pixel group (see Figure 36). Pixels with the same name are controlled simultaneously in the whole pixel-field. More precisely, pixels in the upper and lower rows are controlled simultaneously during measurement, pixels in the even and odd columns are controlled simultaneously during readout.

The pixel group architecture allows the epc660 to operate the pixel-field in different modes and in combinations thereof according the following chapters.

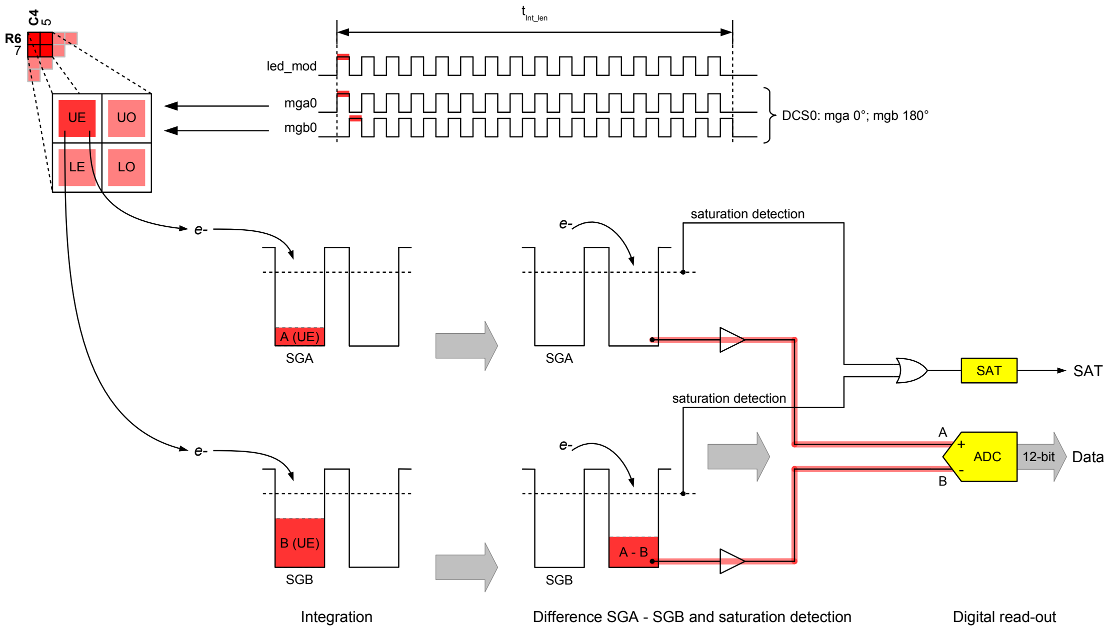


Figure 36: The 2x2 pixel group and the simplified function overview

Each pixel of the pixel group has its own pair of storage gates SGA and SGB. During the integration time, they accumulate the charges (e-) created by the reflected modulated light coming from the object (see section 9, Imaging). They are controlled by the mga and mgb demodulation signals. After the measurement is finished, the readout phase starts. The charges stored in the storage gates SGA and SGB are read out as a difference A – B (ambient-light suppression) and converted into a single 12-bit digital value and a 1 bit saturation flag. The output value can be either positive or negative depending on the demodulated phase and the offset of the signal chain.

7.1. Pixel coordinates

The epc660 pixel-field consists of a total of 328 x 252 pixels whereas 320 x 240 are active. 4 rows top/bottom and 6 columns left/right on the periphery of the pixel-field contain dummy pixels. The upper-left corner (top view on chip) is the origin (4/6) of the epc660 pixel-field. X-axis starts at 4 and counts up to 323 to the right. Pixel y-axis starts at 6 and counts up to 245 to the bottom. All readout modes and control registers use this coordinate system to set or change modes of the chip.

The pixel-field is split vertically into top and bottom. The data read-out is in parallel top and bottom to double the frame rate. It starts in the middle of the row axis. Thus the higher the row number the more dark current is collected by the pixels which appears like an increased DC offset of the pixel value (refer to chapter 1.4). The internal readout of a row is split in two sections: first all even pixels; second all odd pixels. Later on the TCMI interface presents the row in the regular order with even and odd pixels mixed.

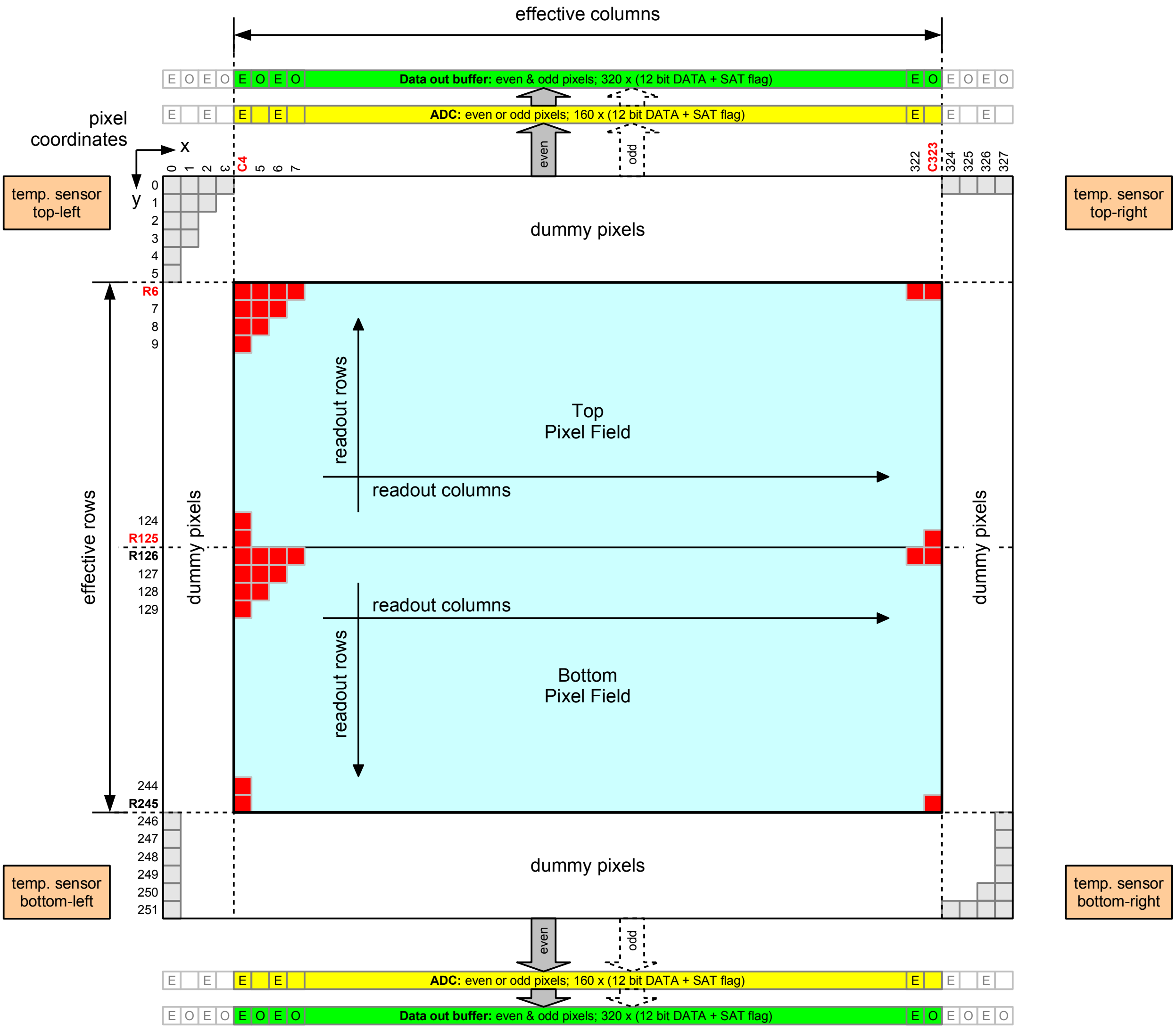


Figure 37: Pixel-field coordinates with row and column numbering scheme (top-view, solder balls are bottom side)

7.2. Pixel saturation detection

The pixels collect continuously modulated and non-modulated ambient light during the integration period. Depending on these light intensities, the pixels may collect more charge (over-exposure) than they can accommodate in their storage gates (refer to Figure 36). In such a case, the 12 bit sample data is not valid and cannot be used for distance calculation.

7.2.1. Hardware saturation flag

Each pixel generates a "saturation detection" flag along with the sample data, so that the data can be discarded by the application. The saturation flag is transmitted via XSYNC_SAT pin with every pixel.

7.2.2. Software saturation flag

If XSYNC_SAT pin is used for an another function by setting register 0xCC, bit 6, bit 7 in register 0xCC enables to drive all DATA[11:0] to 0xFFF when the pixel is saturated.

8. Operation modes

8.1. Full resolution mode (default)

This is the default operation mode for 3D TOF operation. All UE, UO, LE, LO storage gates work simultaneously during measurement operation. The storage gate control signals mga, mgb are applied to all pixels simultaneously (see Figure 38). One, two or four DCS can be acquired in this mode.

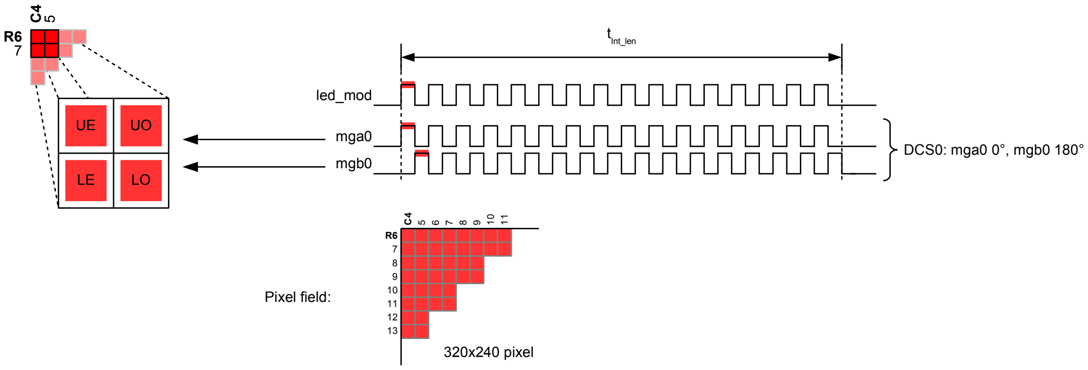


Figure 38: Full resolution mode: even and odd pixel rows are controlled identically with mgx0

8.2. Dual phase mode (motion blur reduction)

In this mode, the odd and even rows are controlled by 90° phase shifted signals (see Figure 39). This mode allows to acquire two 90° shifted DCSs at the same time, e.g. DCS0 and DCS1. In the two-DCS mode, distance calculation can be accomplished within one acquisition. Thus, motion blur is eliminated. The even row pixels store DCS0 (or DCS2) while the odd row pixels store DCS1 (or DCS3). The vertical pixel pairs (e.g. UE/LE) must be treated for distance calculation as if they are one single pixel. This comes at the cost of a reduced resolution along the y-axis. The result provides a total of 320x240 pixel-field readout with an effective 3D TOF resolution of 240x120 pixel. It is worth mentioning that the two middle rows have the same phase and it alternates from there.

Select this mode according chapter 11.4.1.

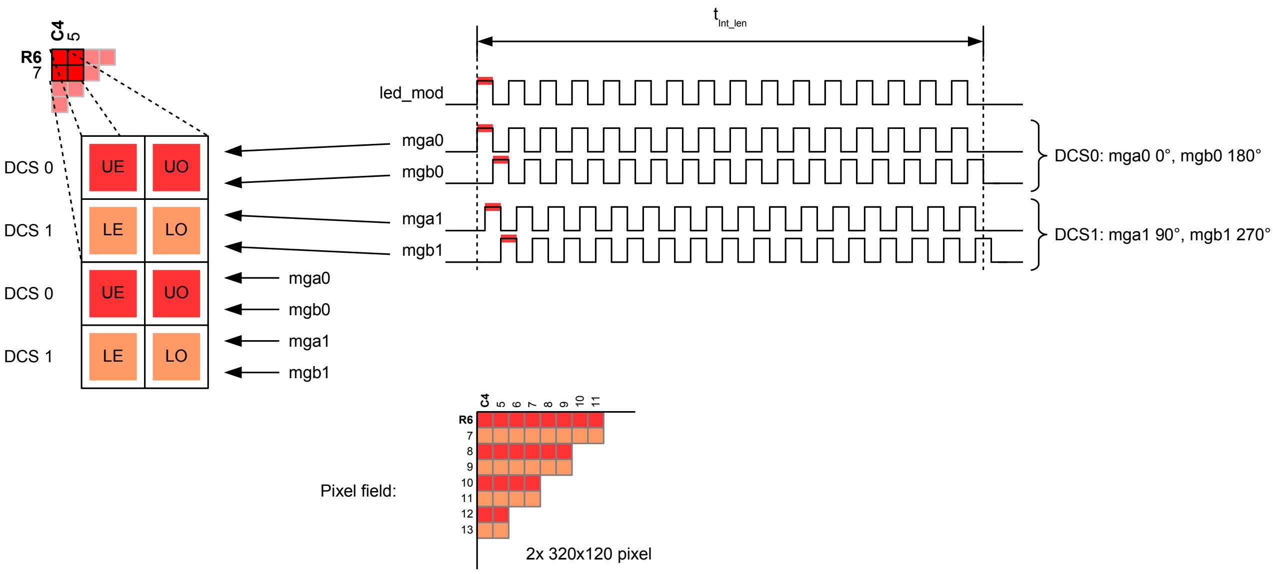


Figure 39: Dual phase mode with phase-shifted integration time:
even and odd rows independently controlled by mgx0 and mgx1 with different phase shifts

IMPORTANT: This mode requires that adjacent pixels look to the same point on the target and receive the same amount of light. Otherwise, calculated distance values are not reliable.
Pixel with a big offset or defective pixel will lead to completely wrong distance values with its paired pixel.
Thus, the pixel group has to be discarded.

8.3. Dual integration time mode (high dynamic range, HDR mode)

In this mode, the odd and even rows are controlled by different integration time lengths. It allows to acquire one image with two different integration times in order to increase the dynamic range. Both groups provide exactly the same DCS modulation signals (phases). One stops earlier than the other due to different integration times (see Figure 40). As a consequence, the two pixels collect different amount of light simultaneously. There is no restriction about which integration time is shorter or longer with respect to the other. The even row pixels integrate with integration length 1, register 0xA2 and 0xA3 while the odd row pixels integrate with integration length 2, register 0x9E and 0x9F. At the transition between the upper and lower pixel field are two columns with the same integration time. The even and odd pixels (e.g. UE, LE) must be used independently for distance calculation. Finally, the vertical pixel pairs (e.g. UE/LE) must be treated as if they are one single pixel by using only the better of the two pixel signals. This comes at the cost of a reduced resolution along the y-axis. Instead of one frame with 320x240 pixels, a single readout provides two DCS or black and white frames with an effective resolution of 320x120 pixels but with different integration times.

Select this mode according chapter 11.4.2.

IMPORTANT: Crosstalk will occur if there is a large difference between the selected integration times. We recommend not to go beyond the factor of 5.

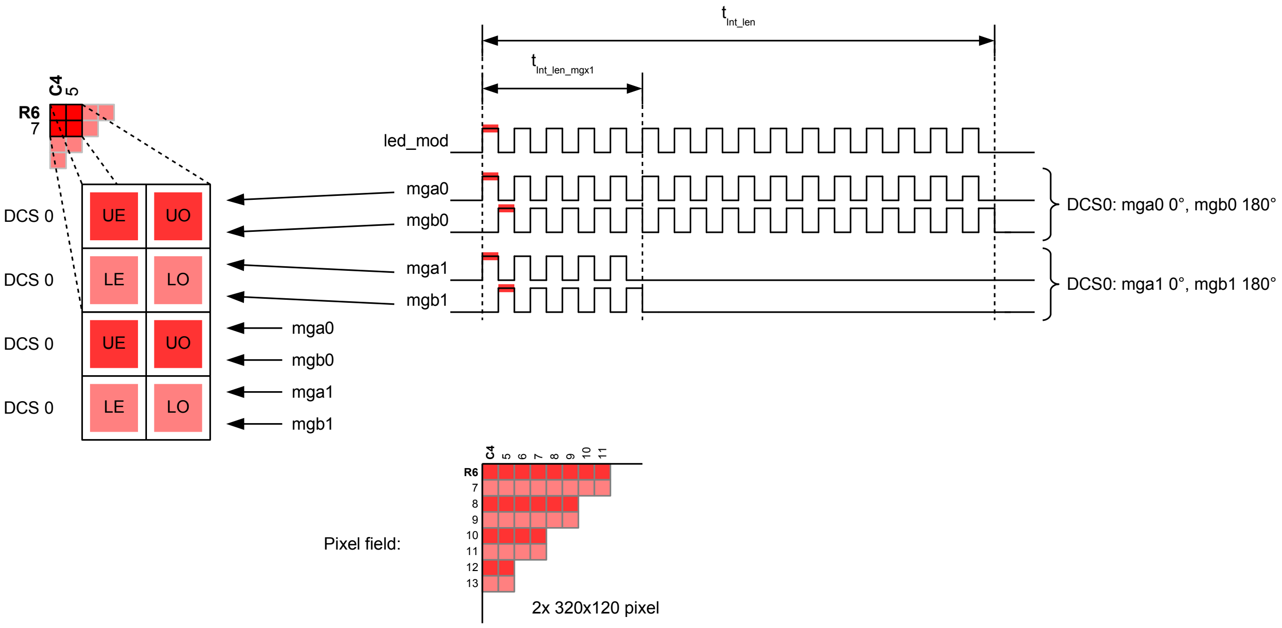
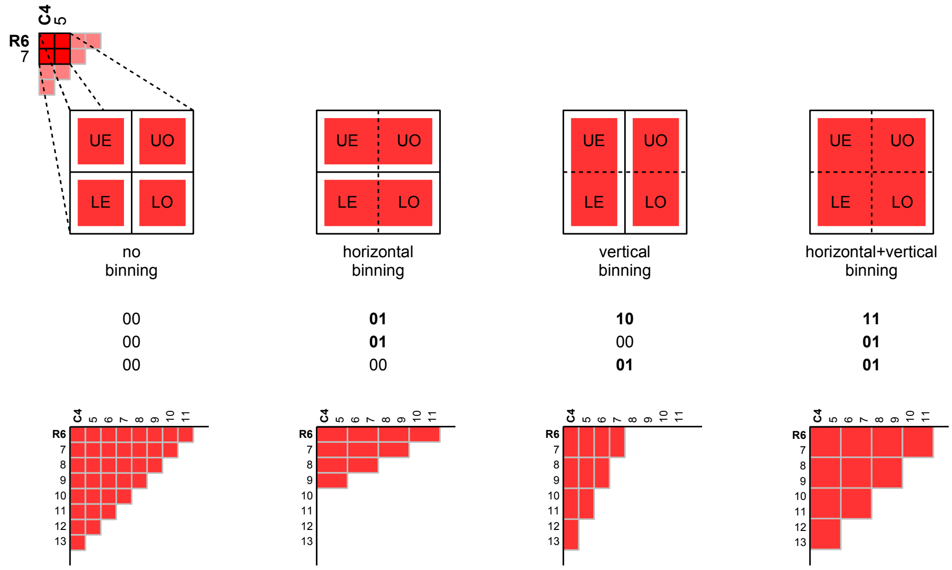


Figure 40: Dual integration time mode:
even and odd rows independently controlled by mgx0 and mgx1. One stops earlier than the other.

8.4. Pixel binning

The charges accumulated in the storage gates during integration can be combined by binning: horizontal, vertical or both (see Figure 41).

IMPORTANT: Increases pixel to pixel noise, only internally recommended
Offers higher sensitivity, reduced integration time and faster readout of frames
Binning requires corresponding resolution reduction being enabled the same time. Refer to register 0x94.
Binning cannot be used with dual phase and dual integration time mode.



	no binning	horizontal binning	vertical binning	horizontal+vertical binning
Pixel group:				
Mode setting:	no binning	horizontal binning	vertical binning	horizontal+vertical binning
Register 0x94:				
Pixel binning =	00	**01**	**10**	**11**
Column reduction =	00	**01**	00	**01**
Row reduction =	00	00	**01**	**01**
Pixel field:				
Reduction of pixel field resolution:	320 x 240	160 x 240	320 x 120	160 x 120
Increase of sensitivity:	1 x	2 x	2 x	4 x
Increase of ratio signal to shot-noise:	1 x	$\sqrt{2}$ x	$\sqrt{2}$ x	2 x
Decrease of DCS frame readout time:	1 x	1/2 x	1/2 x	1/4 x
Increase of DCS frame rate:	1 x	2 x	2 x	4 x

Figure 41: Pixel binning modes and readout

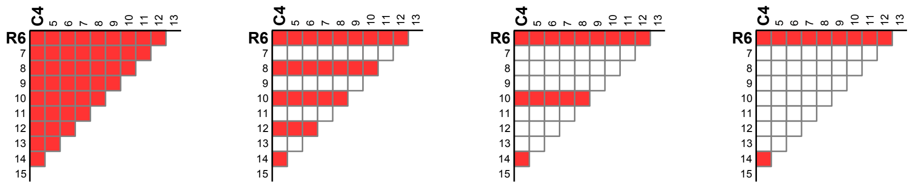
8.5. Resolution reduction

Resolution reductions by reading only every 2nd column on x-axis and every 2nd , 4th and 8th row on y-axis are supported independently. It can be combined with binning (see chapter before), ROI (see next chapter), motion blur reduction and high dynamic range modes. See Figure 42 - Figure 47 for example combinations.

IMPORTANT: Dual phase and dual integration time modes can be used with resolution reduction only, not with binning.

Resolution reduction shrinks the dataset to the necessary amount of data required for the application. The advantages are the reduced amount of data to be processed for the final measurement result (reduced frame buffers) and the faster processing (shorter readout and processing time).

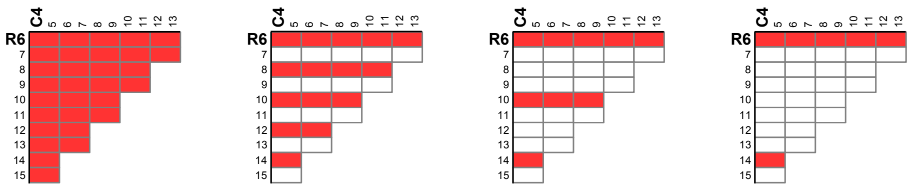
Register 0x94:				
Pixel binning =	00	00	00	00
Column reduction =	00	00	00	00
Row reduction =	00	**01**	**10**	**11**



Pixel field resolution:	320 x 240	320 x 120	320 x 60	320 x 30
Frame rate:	1x	2x	4x	8x

Figure 42: Row reduction on y-axis without binning

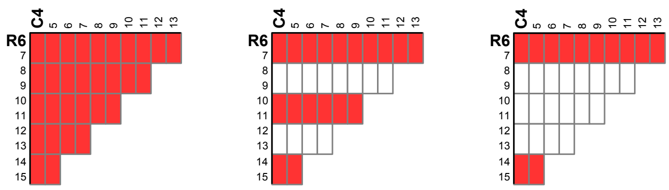
Register 0x94:				
Pixel binning =	**01**	**01**	**01**	**01**
Column reduction =	**01**	**01**	**01**	**01**
Row reduction =	00	**01**	**10**	**11**



Pixel field resolution:	160 x 240	160 x 120	160 x 60	160 x 30
Frame rate:	2x	4x	8x	16x

Figure 43: Row reduction on y-axis combined with horizontal binning

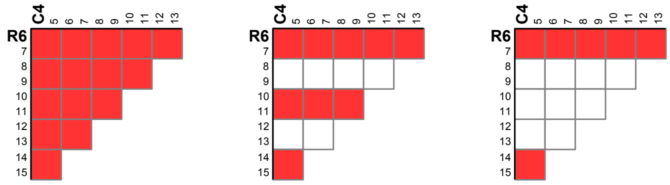
Register 0x94:			
Pixel binning =	**10**	**10**	**10**
Column reduction =	00	00	00
Row reduction =	**01**	**10**	**11**



Pixel field resolution:	320 x 120	320 x 60	320 x 30
Frame rate:	2x	4x	8x

Figure 44: Row reduction on y-axis combined with vertical binning

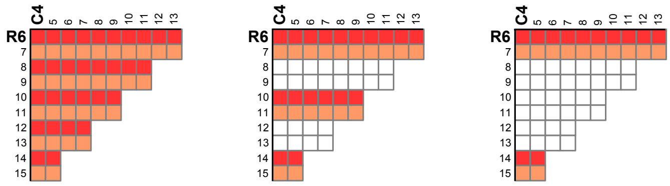
Register 0x94:			
Pixel binning =	**11**	**11**	**11**
Column reduction =	**01**	**01**	**01**
Row reduction =	**01**	**10**	**11**



Pixel field resolution:	160 x 120	160 x 60	160 x 30
Frame rate:	4x	8x	16x

Figure 45: Row reduction on y-axis combined with horizontal and vertical binning

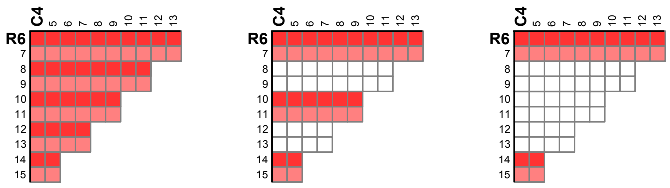
Register 0x94:			
Dual MGX mode =	**1**	**1**	**1**
Pixel binning =	00	00	00
Column reduction =	00	00	00
Row reduction =	00	**01**	**10**



Pixel field resolution:	2 x 320 x 120	2 x 320 x 60	2 x 320 x 30
Frame rate:	1x	2x	4x

Figure 46: Row reduction on y-axis combined dual phase mode

Register 0x94:			
Dual MGC mode =	**1**	**1**	**1**
Pixel binning =	00	00	00
Column reduction =	00	00	00
Row reduction =	00	**01**	**10**



Pixel field resolution:	2 x 320 x 120	2 x 320 x 60	2 x 320 x 30
Frame rate:	1x	2x	4x

Figure 47: Row reduction on y-axis combined with dual integration time mode.

8.6. Region of interest (ROI)

The ROI allows readout and transfer the portion of the pixel-field data which is necessary for an application. The advantages are same as for the resolution reduction: Reduced amount of data which have to be readout and processed. For integration times in the µs range, much shorter than the row conversion time (see Figure 29), the frame rate scales with the set number of rows of the ROI.

ROI is active always and works mirrored over the top and bottom pixel-fields. The symmetric part in the bottom pixel-field is generated simultaneously. Therefore, only minimum top-left [C4,R6] and the maximum bottom-right [C323,R125] coordinates in the top pixel-field need to be set (registers 0x96 – 0x9B). The ROI starts with even row and column and ends with odd row and column. Top-left coordinates are smaller than the bottom-right.

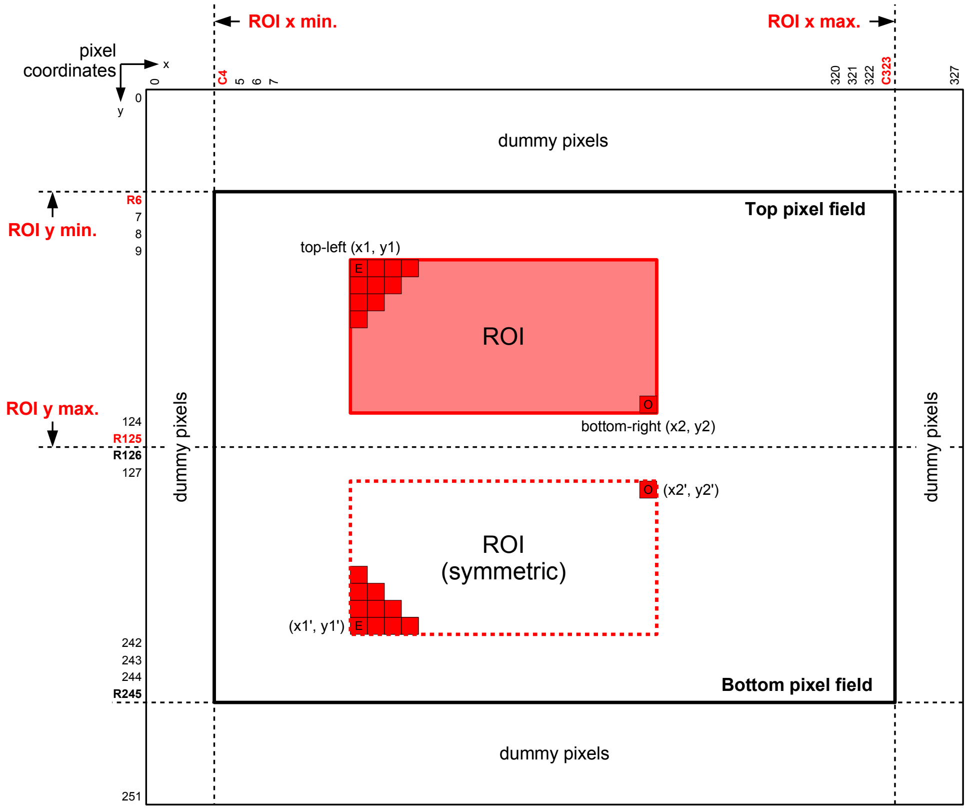


Figure 48: Region of interest (ROI)

The ROI registers can be changed on-the-fly via I^{2}C all the time. The new values will be used with the next frame start. The application must use the same ROI during the data readout.

IMPORTANT:

1. ROI can be set to a minimum rectangle of columns by rows of 6 by 2.
2. If row reduction is enabled, the minimum number of ROI rows is inversely scaled, e.g.: **row reduction by 2** makes the minimum ROI to 6 by **4**.
3. If column reduction is enabled, the minimum number of ROI columns is inversely scaled, e.g.: **column reduction by 2** makes the minimum ROI to **12** by 2.

9. Imaging

9.1. Distance measurement (3D TOF)

The epc660's default modulation mode is based on the sinusoidal TOF modulation theory but uses effectively for the illumination a square-wave modulated signal with a duty cycle of 50%. After reset, all internal register values are default to operate the chip at 4MHz XTAL/external clock input, multiplied up to 48MHz at the PLL output, clocks the modulator with 48MHz modulation clock (mod_clk), modulates LED/LD with 12MHz and acquires 4 successive DCS frames (0 ... 3) using 47.6µs integration time.

The distance measurement mode uses the on chip LED driver and the external LED/LD to provide modulated light on the target. Modulation control signals to the LED driver are provided by a programmable modulator. The modulator generates all signals to modulate the external LED/LD and simultaneously all demodulation signals to the pixel-field. TOF and grayscale mode with all the variants are generated here.

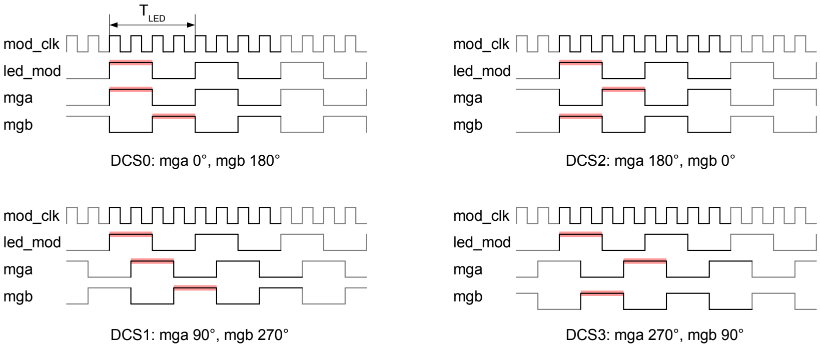


Figure 49: 4 DCS modulation/demodulation waveforms

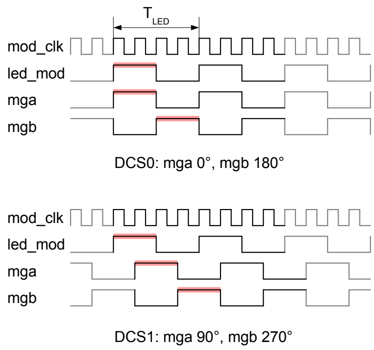


Figure 50: 2 DCS mod./demod. waveforms

The modulation table registers 0x22 … 0x2D control the modulation (refer to Table 35). The registers can be updated via I²C bus between frame acquisitions. The application must take care that the last frame's integration phase is completed before modifying these registers on the fly. This time can be detected by the application by waiting for the falling-edge of VSYNC or the first falling-edge of HSYNC signal after shutter pulse/command was applied. This allows to run continuously at the maximum frame rate. For a full-frame readout, the margin is a 3.6ms to alter these registers via I²C on the fly.

With the application of the shutter pulse (HW SHUTTER or SW shutter via I²C), the chip performs the required number of successive DCS acquisitions. Each one of the 4 DCS frame types has a different phase relation between modulation (led_mod) and demodulation (mga, mgb) signals which makes phase-to-distance calculation possible. In case of DCS0, led_mod is phase-shifted by 0º and 180º with respect to mga and mgb, respectively. In case of DCS1, led_mod is phase-shifted by 90º and 270º. For DCS2, the phase shifts are 180º and 0º and for DCS3, the phase shifts are 270º and 90º (see Figure 49). Note that for DCS2 and DCS3, the demodulation signals mga and mgb are simply swapped with respect to DCS0 and DCS1, respectively.

By programming the number of DCS readouts = 01 (see 0x92 register), shutter initiates 2 successive DCS frame acquisitions (see Figure 50). This mode allows distance acquisition by using two DCSs only and thus a doubled frame rate. However, the cost is a lower distance measurement accuracy and a 40% higher distance noise.

9.2. Distance calculation algorithm

The use of the trigonometric atan2 definition for vectors (x, y) in the Cartesian coordinate system φ = atan2(x, y) = atan2(y/x) guarantees a continuous distance calculation algorithm in the range of phases between -π … +π. In our case, we use the range from 0º… 360º which corresponds to the distance from 0m up to the unambiguity distance (refer to Figure 51 and Figure 52).

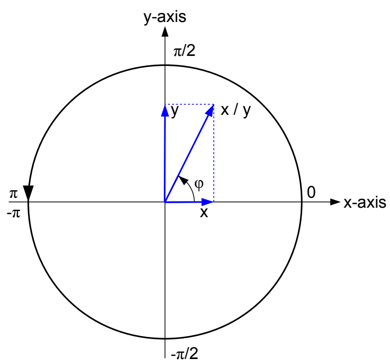


Figure 51: Continuous atan2 representation for the range -π … +π

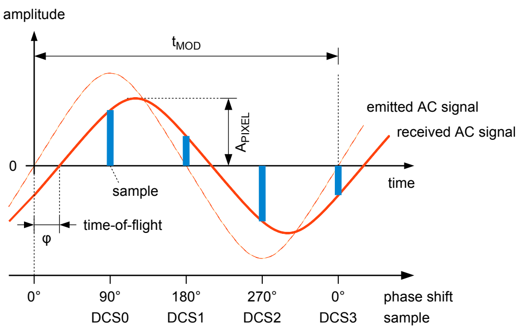


Figure 52: Sampling of the received waveform

Typically, the distance is calculated by using the 4 DCSs, also called π-delay matching, which cancels pixels offsets leading to distance errors:

$$[2] \quad D_{TOF}\,[m] = \frac{c}{2} \cdot \frac{1}{2\pi f_{LED}} \cdot \left[\pi + \mathrm{atan2}\left(\frac{DCS3-DCS1}{DCS2-DCS0}\right)\right] + D_{OFFSET}$$

The measured data are always over the 360° phase-shift valid. Due to the distance offset adjustment D_{OFFSET}, the correction of the distance roll-over effect at zero and unambiguity distance is necessary for having all the time correct distance values D:

- if $D_{TOF} > D_{Unambiguity}$: $D = D_{TOF} - D_{Unambiguity}$
- if $D_{TOF} < 0$: $D = D_{TOF} + D_{Unambiguity}$
- else: $D = D_{TOF}$

If higher distance errors can be tolerated but a high frame rate is needed, the distance calculation also works with 2 DCSs only:

$$[3] \quad D_{TOF}[m] = \frac{c}{2} \cdot \frac{1}{2\pi f_{LED}} \cdot \left[\pi + \operatorname{atan2}\left(\frac{-DCS1}{-DCS0}\right)\right]$$

The following terms are used in the formulas above:

D_{TOF}	Distance in meters [m]
c	Speed of light 299'792'458 [m/s]
f_{LED}	LED/LD modulation frequency e.g. 12MHz
DCS0 - DCS3	Sampling amplitude [LSB]
φ	Phase shift caused by the time-of-flight [rad]
D_{OFFSET}	Offset compensation [m]
$D_{Unambiguity}$	Unambiguity distance

9.2.1. Unambiguity range versus time base setting

Due to continuous modulation, roll-over can be observed if the distance to the object is longer than the length of one modulation cycle (one period, 2π). This roll-over distance is called unambiguity range can be calculated as follows:

$$[4] \quad D_{Unambiguity}[m] = \frac{c}{2} \cdot \frac{1}{f_{LED}}$$

The operating range is the maximum distance which corresponds to the maximum time-of-flight inside of one period of the used modulation: It is one period of f_{LED}. Objects inside this area are detected unambiguously.

The unambiguity range defines the repetition distance, where objects outside of the targeted operating range can still be detected as far they are of very high reflectivity (remission). Strongly reflected signals outside of this range may therefore interfere with the measurement.

The operating range, the unambiguity distance, the time base for the integration time and the resolution of the distance signal are defined by the modulation clock mod_clk. This corresponds for the epc660 to a maximum default operating range of 12.5m @ mod_clk = 43MHz. It may be necessary depending on the application to adapt these parameters to other values. It can be done by a change of the modulation clock. Table 20 lists as an example some values of the modulation clocks in function of the the unambiguity distances, of the distance resolutions and of the multipliers of the integration time base.

Unambiguity distance	Integration time multiplied by	Distance resolution [2]	Modulation clock	Modulation clock divider	LED modulation frequency
			f_{MOD}	Register 0x85	f_{LED}
[m]	[#]	[cm]	[MHz]	[#]	[MHz]
6.25	1	0.21	96	0	24
12.5 [1]	2 [1]	0.42	48	1 [1]	12
25	4	0.83	24	3	6
50	8	1.67	12	7	3
100	16	3.33	6	15	1.5

Table 20: Unambiguity range versus on-chip modulation clock

Notes:

[1] Default values

[2] The distance resolution is given for an operating range corresponding to 3'000 LSB.

[3] Using external modulation clock MODCLK: Follow chapter 5.5.

9.2.2. Quality of the measurement result

The DCS values contain not only the distance information, but also the quality and the validity (confidence level) of the received optical signal. The higher the signal amplitude of the received signal, the better and more precise the distance measurement. Each distance measurement of every pixel has its own validity and quality.

The primary quality indicator for the measured distance data is the amplitude of the received modulated light A_{TOF}. The amplitude is in direct relationship to the distance noise (refer to Figure 5). The amplitude can be calculated as follows:

$$[5] \quad A_{TOF} = \frac{\sqrt{(DCS2 - DCS0)^2 + (DCS3 - DCS1)^2}}{2}$$

Amplitude A_{TOF}	Classification	Action
< 25 LSB	Weak illumination	Objects can be detected but distance measurement is not possible. Increase the integration time for the next measurement.
25 … 100 LSB	Useful for measurement	High distance noise, increase the integration time
100 … 1'700 LSB	Good signal strength	No action necessary
> 1'700 LSB	Overexposed	Decrease integration time for the next measurement.

Table 21: Signal amplitude versus classification

Note:
The amplitude value is the feedback parameter that is used to set the integration time for the next measurement. Generally, the higher the received signal, the better and more precise the distance measurement.

9.3. Grayscale imaging

The grayscale mode allows using the epc660 as a grayscale imager. This mode can be used either without LED/LD illumination for ambient-light measurements or with LED/LD for active illumination of the scenery. The grayscale measurement uses regular DCS measurement but with DCS0 only. It is performed with differential readout using MGA only which stays on all the integration time. Data output format is signed integer 12 bit: ± 2'047 LSB. Effective data range is 0 … +2'047. Due to system noise around zero, the readout can show small negative numbers. Corresponding settings can be found in register 0x3C (= 0x26). Due to fact that distance measurement results can be influenced by ambient-light, the grayscale measurement without illumination can thereof be used as an important quality and correction parameter for the distance measurement.

The saturation flag status is invalid in this mode.

The irradiance E_{BW} of the grayscale signal at the surface of a pixel can be calculated from the DC sensitivity S_{BW}, the used integration time t_{INT-BW}, the reference integration time $t_{INT-REF-BW}$ and the amplitude of DCS0 of the grayscale signal as follows:

$$[6] \quad E_{BW} = S_{BW} \cdot \frac{t_{INT-REF-BW}}{t_{INT-BW}} \cdot DCS0 \qquad \text{e.g.} \quad E_{BW} = 0.25 \frac{nW/mm^2}{LSB} \cdot \frac{100\mu s}{1.6\mu s} \cdot 1'000\ LSB = 15.6\mu W/mm^2$$

9.4. Calibration and compensation of TOF cameras

This modern TOF sensor chip offers a fully digital interface to the control circuitry of a TOF camera. The first time, user naturally expects straight forward implementation and digital accuracy of the measured signals. Unfortunately, this is often followed by tremendous disillusion because of the many physical effects influencing the final performance of 3D TOF cameras.

3D TOF cameras capture images by utilizing the time-of-flight measurement of photons. Photons are emitted by high frequency modulated LEDs or laserdiodes, which are part of the camera, then scattered from objects in the scenery and finally, some of the emitted photons are reflected back to the camera and captured in so-called demodulation pixels. This time-of-flight happens in an incredibly short period of time as it takes place with 300'000km/s or 30cm/ns. If one would like to achieve a centimeter distance resolution and accuracy, 30ps time measurement accuracy has to be achieved. This is a very tough requirement, especially if tens of thousands of pixels shall provide such accurate measurement several dozen times per second at the same time. Small and inherent differences in the connection and arrangement of transistors within the TOF chip, temperature differences and changes, but also irradiance signal strength and last but not least ambient light change lead to measurement errors in the tens of centimeters:

Calibration and compensation is essential to reach the goal. To support users, ESPROS issued on the Website www.espros.com in the section "Downloads" the application note AN10 "Calibration and compensation of Cameras using ESPROS TOF Chips". This paper describes the error sources in 3D TOF sensor chips, a simple way to implement a calibration procedure and how to compensate them on camera level.

Other documents which can be helpful to achieve a successful implementation of the chip are listed in chapter 16.2, Related documents.

9.5. Noise reduction and signal filtering

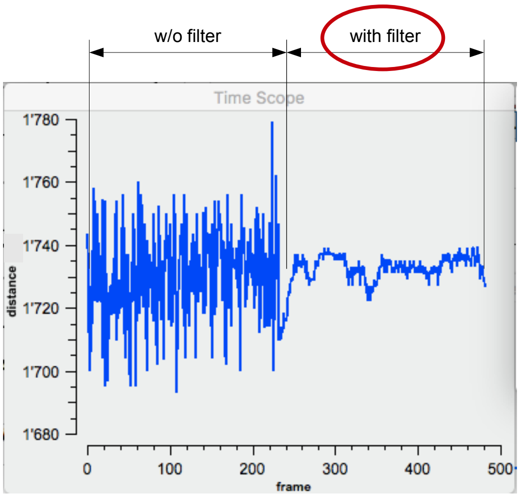


Figure 53: Effect of the static Kalman filter on distance noise (Distance in mm)

Whatever measurement process is applied, distance noise is one of the major challenging factors of 3D TOF imaging. It limits to distinguish in depth between small objects or fine contours. It is called temporal noise and varies from measurement to measurement. Since this noise is a statistical value, its effect can be reduced by filtering.

However, a simple averaging with a FIR filter is not suitable in many applications because of the very long time lag to get a filtered result. Filtering based on the theory of Rudolf E. Kalman, noise can be reduced significantly without losing responsivity of the system. Figure 53 shows the resulting effect of such a Kalman filter.

Left side: The frames 0 to 120 have been acquired without filtering at all. The distance noise is approx. 12cmpp (1 sigma = 2.5cm).
Right side: Frames 121 to 250 are processed with the Kalman filter. The distance noise is reduced to approx. 2cmpp (1 sigma = 0.5cm).
The signal amplitude was quite low in both cases, approx. 250 LSB.

To support users, ESPROS issued on the Website www.espros.com in the section “Downloads” the application note AN12 “Distance Noise Reduction with Kalman Filter”. This paper describes background and implementation of two Kalman filter algorithms in 3D TOF cameras.

10. Temperature sensors

There are four temperature sensors located near the pixel-field (Figure 3). They are factory calibrated at 27°C (offset). The temperature values can be accessed in registers 0x60 - 0x67 after taking a grayscale image. The sensitivity for taking the grayscale image with the procedure described below is 2.5 times lower compared to the regular grayscale modes described in chapter 9.3. Most applications need grayscale (or ambient-light) pictures for background-light compensation. By reading the temperature, a grayscale image can be read at the same time.

10.1. Initialization

upon power-up or after a RESET:

```
define V, W, X, Y, M,                # Define required variables
       array_C[4], array_Z[4],       # Define required variables
       array_TH[4], array_TL[4],     # Define required variables, only for temperature reading
       Temp[4]                       # Define required variables

V = RD @0xD3                         # Save register 0xD3
W = RD @0xD5                         # Save register 0xD5
X = RD @0xDA                         # Save register 0xDA
Y = RD @0xDC                         # Save register 0xDC

array_C[0] = RD @0xE8                # Read sensor top-left factory calibration
array_C[1] = RD @0xEA                # Read sensor top-right factory calibration
array_C[2] = RD @0xEC                # Read sensor bottom-left factory calibration
array_C[3] = RD @0xEE                # Read sensor bottom-right factory calibration

# Calculate for i = 0,1,2,3
array_Z[i] = array_C[i]/4.7-0x12B    # Normalized calibration values for the temperature formula

#Set defaults for grayscale
WR @0x3C = 0x26                      # Ambient only (default factory setting)
WR @0x3A = 0x30                      # Differential readout
```

Note:
The registers 0xD3, 0xD5, 0xDA, 0xDC are factory set registers (trim registers). To achieve an optimal temperature sensing, these registers have to be modified before temperature reading. Afterwards, their original contents have to be restored. This procedure is described above. If these registers are accidentally overwritten, the chip will not work anymore properly. However, the original content of these registers is stored in the EEPROM. By applying a reset, the original content is restored and the chip will work as expected.

10.2. Readout during runtime

1. Set the integration time for the grayscale image the regular way. Note: The sensitivity is 2.5 times lower than in the regular grayscale mode.
2. Acquire a grayscale image, do the temperature readout and the temperature calculation. The grayscale image will be acquired with the following procedure and stores the temperature value into the registers 0x60 … 0x67.

```
M = RD @0x92                         # Save mode register, control no. of DCS

WR @0xD3 = V or 0x60                 # Set bits b5 and b6
WR @0xD5 = W and 0x0F                # Clear bits b4 and b5
WR @0xDA = X or 0x60                 # Set bits b5 and b6
WR @0xDC = Y and 0x0F                # Clear bits b4 and b5

# Image acquisition
WR @0x92 = 0xC4                      # Change mode to grayscale
WR @0xA4 = 0x01                      # Trigger image acquisition
                                     # (can also be done with a hardware shutter pulse)

# Wait until the image is transferred (VSYNC goes high)
array_TH[0] = RD @0x60               # Read sensor top-left high byte
array_TL[0] = RD @0x61               # Read sensor top-left low byte
array_TH[1] = RD @0x62               # Read sensor top-right high byte
array_TL[1] = RD @0x63               # Read sensor top-right low byte
array_TH[2] = RD @0x64               # Read sensor bottom-left high byte
array_TL[2] = RD @0x65               # Read sensor bottom-left low byte
```

```
array_TH[3] = RD @0x66              # Read sensor bottom-right high byte
array_TL[3] = RD @0x67              # Read sensor bottom-right low byte

# Switch back to normal image acquisition
WR @0xD3 = V                        # Restore register 0xD3
WR @0xD5 = W                        # Restore register 0xD5
WR @0xDA = X                        # Restore register 0xDA
WR @0xDC = Y                        # Restore register 0xDC
WR @0x92 = M                        # Change back to the mode before temperature reading
```

10.3. Calculate temperature in °C

```
#i = 0,1,2,3
Temp[i] = (array_TH[i]*0x0100+array_TL[i]-0x2000)*0.134+array_Z[i]

#Temp[0]: Sensor top-left temperature
#Temp[1]: Sensor top-right temperature
#Temp[2]: Sensor bottom-left temperature
#Temp[3]: Sensor bottom-right temperature
```

Note:
The grayscale image which has been acquired can be used. However, the sensitivity during this acquisition was reduced by a factor of 2.5. Thus, if the same sensitivity should be needed, the integration time has to be increased with a multiplier of 2.5.

In order to reduce temporal noise on the temperature measurement, the following filtering algorithm is recommended.

1. Spatial averaging over the 4 temperature sensors.
2. Temporal filtering with a Kalman filter.

```
x[i] = (Temp[0]+Temp[1]+Temp[2]+Temp[3])/4  # Spatial averaging

k = 0.1                                     # Kalman gain
y[i-1] = x[0]                               # Start condition

y[i]=k*x[i]+(1–k)*y[i-1]                    # Simple Kalman filter
```

x[i]: Current spatial averaged temperature
y[i]: Current temporal filtered temperature
y[i-1]: Previous temporal filtered temperature

11. Application information

11.1. Start-up and initialization sequence

11.1.1. Default

1. $\overline{\text{RESET}}$ = 0.
2. Apply all supplies (chapter 5.6.1).
3. $\overline{\text{RESET}}$ = 1.
4. Continue when copying from EEPROM to CFG is finished.
5. Write pixel sequencer code to memory (chapter 15.11)
6. Enable LED preheat (chapter 1.6).
7. Set registers as shown in 22:

Address	Set to	Comments
0x7E	bit 0 = 1	Read this register for a feedback if EEPROM to CFG copied
0x90	bit 3 = 1	Enable LED Preheat
0xAB	0x01	
0xAE	0x04	Enable manual DLL control

Table 22: Additional register settings during startup

11.1.2. Customer specific

- Set modulation clock to external.
- Set custom I^{2}C slave address with strap pins (chapter 5.6.3).
- Set TCMI mode and polarity.
- Set integrated LED driver according to used illumination.
- The registers as shown in 23:

Address	Comments
0x80	Enable internal clk and external modulation clock. Set therefore address 0x80 to 0x7F.
0xCB	I^{2}C and TCMI control
0xCC	TCMI polarity settings
0x90	LED/LED2 driver control

Table 23: Customer specific register

11.2. Image acquisition

11.2.1. 3D TOF mode

- Select acquisition mode:
- Set registers as shown in 24:

Address	Set to	Comments
0x92	0x34	4 DCS TOF mode
0x92	0x1C	2 DCS TOF mode

Table 24: Register settings for DCS mode

11.2.2. Grayscale mode

- Enable Grayscale mode
- Differential readout with ABS
- Adjust the saturation threshold to get a better image. Important: Set it back for taking a 3D TOF image.
- Switch to temperature sensing mode
- Set registers as shown in 25:

Address	Set to	Comments
0x92	0xC4	Change mode to grayscale
0x3A	0x30	Select readout mode to ABS
0xAF	0x39	Saturation threshold for 125us integration time
0xD3 - 0xDC		Temperature sensing mode according to chapter 10.2

Table 25: Additional register settings during grayscale mode

11.2.3. Dual phase mode selection (motion blur reduction)

Refer for the description to chapter 8.2.

- This mode needs the following basic setting of the register 0x94 = 0x80, register 0x22 = 0x34 and register 0x25 = 0x3E.
- Reset the registers to the default values after leaving this mode: register 0x94 = 0x00, register 0x22 = 0x30 and register 0x25 = 0x35.

Function	Register 0x92	Comments
4x DCS	not applicable	
2x DCS [2]	0x14	Output is effectively 4x DCS in 2 DCS-frames.
Grayscale	not applicable	

Table 26: Setting basic dual phase mode

11.2.4. Dual integration time mode selection (high dynamic range)

Refer for the description to chapter 8.3.

- This mode needs the following basic setting of the register 0x94 = 0x80.
- Reset the register to the default value after leaving this mode: register 0x94 = 0x00.
- Output is 2 equal DCS frames with different integration times in one readout frame.

Mode	Register setting		Comments
Function	Register 0x92	Register 0x3C	
4x DCS	0x3C	0x26	
2x DCS	0x1C	0x26	
Ambient only	0xCC	0x26	Grayscale imaging, no active illumination
Ambient & non modulated LED/LD	0xCC	0x16	Grayscale with DC illumination
Ambient & modulated LED/LD	0xCC	0x06	Grayscale with modulated illumination

Table 27: Setting dual integration time mode for TOF and grayscale

11.3. Configuration sequence

This example shows a normal image acquisition with four DCS and one grayscale image.

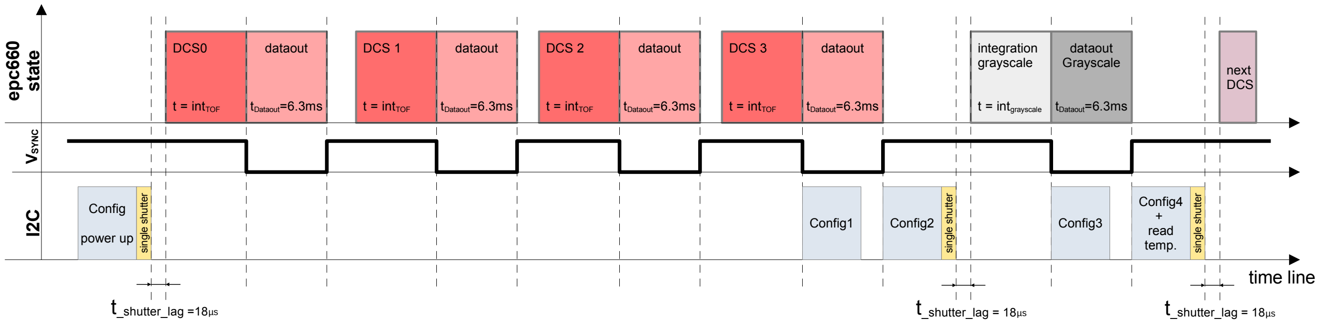


Figure 54: Sequence for normal DCS mode

Table 28: I2C command with description and required time

Action	I2C commands	Comment / description	required time I2C command SCL = 1MHz
Config power up	WR 0x3A = 0x30 WR 0x3C = 0x26 WR 0x85 = 0x01 WR 0xA0, 0xA1, 0xA2, 0xA3 = 0x.. WR 0x92 = 0x34	has to be initialized only once after system power up has to be initialized only once after system power up set modulation frequency with MOD_CLK_divider configure integration time = int_{TOF} Configure 4 DCS mode	29µs (1x I2C write) 29µs (1x I2C write) 29µs (1x I2C write) 4 x 29µs = 116µs (4x I2C w.) 29µs (1x I2C write)
Single shutter	WR 0xA4 = 0x01	a) trigger SW shutter b) trigger HW shutter (faster than SW trigger)	29µs (1x I2C write) HW trigger lag = 3us
Config 1	WR 0x92 = 0xC4 WR 0xA0, 0xA1, 0xA2, 0xA3 = 0x..	configure grayscale mode configure integration time = $int_{grayscale}$	29µs (1x I2C write) 4 x 29µs = 116µs (4x I2C w.)
Config 2	WR 0xD3, 0xD5, 0xDA, 0xDC = 0x..	Modify register values according data sheet (normal sensing mode)	4 x 29µs = 116µs (4x I2C w)
Single shutter	WR 0xA4 = 0x01	a) trigger SW shutter b) trigger HW shutter (faster than SW trigger)	29µs (1x I2C write) HW trigger lag = 3us
Config 3	WR 0xA0, 0xA1, 0xA2, 0xA3 = 0x.. WR 0x92 = 0x34	configure integration time = int_{TOF} Configure 4 DCS mode	4 x 29µs = 116µs (4x I2C w.) 29µs (1x I2C write)
Config 4 + read temp.	WR 0xD3, 0xD5, 0xDA, 0xDC = 0x.. RD 0x60, 0x61, … , 0x67	Modify register values according data sheet (temper-ature sensing mode) get values for temperature calculation	4 x 29µs = 116µs (4x I2C w.) 8 x 39µs = 312µs (4x I2C r.)
Single shutter	WR 0xA4 = 0x01	a) trigger SW shutter b) trigger HW shutter (faster than SW trigger)	29µs (1x I2C write) HW trigger lag = 3us

NOTE: Config registers can be updated on-the-fly while a frame acquisition is going on. The new values are used at the start of the next frame.

11.4. Integration time setting

The integration time is the active frame acquisition period (see Figure Figure 29). Specially for moving objects or cameras, this time should be as short as possible to reduce or eliminate motion blur effects. The integration time together with the illumination intensity also defines the effective achievable operating distance. Using the on-chip modulation clock, the integration time can be calculated as

$$t_{INT} = \frac{reg(0x85)+1}{96MHz} \cdot [reg(0xA2:0xA3)+1] \cdot reg(0xA0:0xA1) \quad [7]$$

Table Table 29 lists some useful integration time settings.

Integration time	Registers (0xA0:0xA1)		Registers (0xA2:0xA3)	
	[DEC]	[HEX]	[DEC]	[HEX]
1.58 µs	1d	0x0001	75d	0x004B
12.5 µs	1d	0x0001	599d	0x0257
100 µs	1d	0x0001	4'799d	0x12BF
800 µs	1d	0x0001	38'399d	0x95FF
1.6 ms	2d	0x0002	38'399d	0x95FF

Table 29: Typical TOF and grayscale integration times for 12MHz on-chip modulation frequency (modulation clock = 48MHz)

11.5. Power consumption

The epc660 has several power states/levels during the different operation phases which are shown in Table 30 and Figure 55.

Power state	Power [mW]	Operation description
RESET	54	All supplies are ON, $\overline{\text{RESET}}$ = 0, Oscillator is ON, PLL and all system system clocks are OFF
READY	110	$\overline{\text{RESET}}$ = 1, PLL and all system clocks ON, waiting for SHUTTER
INTEGRATION	1'300	SHUTTER pulse/command
CONVERSION	555	Integration finished, conversion of rows
CONVERSION + DATAOUT	580	Transmit row data via TCMI while converting next row
DATAOUT	110	Transmit last row data via TCMI

Table 30: Typical average power consumption levels at different operating states (integration time < 5ms)

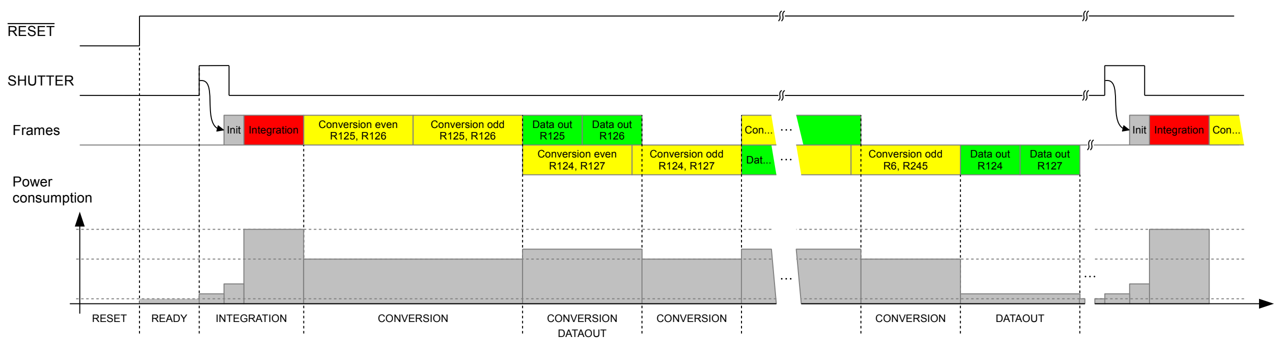


Figure 55: Power consumption levels and operating states

For power critical applications e.g. battery powered systems, it is possible to enforce the epc660 to go in so-called power saving states.

No.	Register			Description
	Name	Address	Value	
Power down				
1	Power control	0xA5	0x00	Switch off of unnecessary supplies
2	Clock control	0x80	0x00	Switch off of unnecessary clocks
3	Mode control	0x7D	0x14	Switch system clock to XTAL clock
4	Mode control	0x7D	0x10	Switch off PLL
Power up				
5	Mode control	0x7D	0x14	Switch on PLL
5	**Wait > 32µs**			**Wait until PLL stable**
7	Mode control	0x7D	0x04	Switch system clock to PLL
8	Clock control	0x80	0x3F	Switch on the clocks again
9	Power control	0xA5	0x07	Switch on the supplies again
10	**Wait until supplies are stable**			
11	**Regular 3D TOF operation**			

Table 31: Sequence for the SW POWER DOWN mode

11.6. Rolling DCS frames

In special applications, it is possible to use all the time the same integration time in continuous distance measurement mode without any grayscale images for ambient-light compensation. Such a set-up allows enhancing the distance measurement rate by a factor of 4 by using rolling DCS frames.

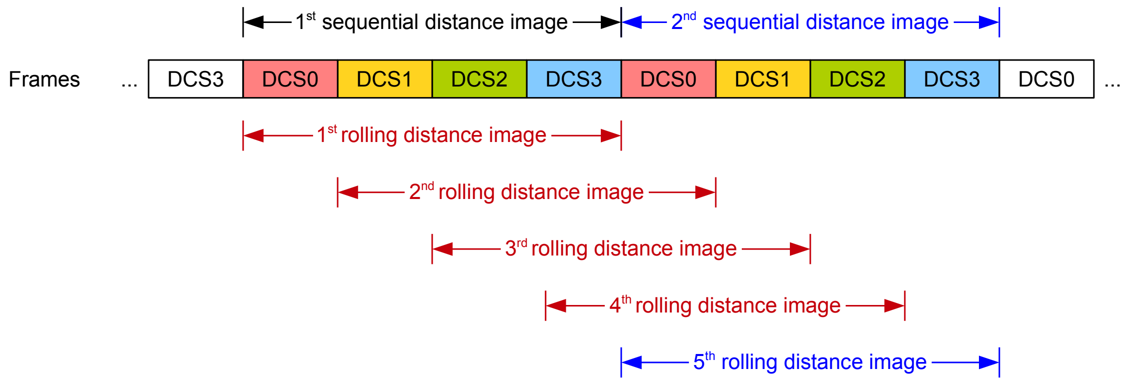


Figure 56: Rolling DCS frames

As shown in Figure 56, the algorithm performs with each new DCS frame a new distance calculation based on the new and last three DCS frames.

11.7. Enhanced rolling DCS frame mode

epc660 allows to set for each single DCS access own parameters. This opens also the possibility to acquire in time-sequence DCSx frames with e.g. different integration times.

The enhanced rolling mode combines all:

The stacking of integration times to enlarge the dynamic range, the acquisition of an ambient-light image for correction and the rolling mode to speed up the frame rate.

The final distance frame acquisition will be in an equidistant time manner e.g. for 2 or more different integration times.

Select out of the acquired integration time distance frames, already compensated, each time the most reliable distance information for the final composed distance picture

The example shown here is using two integration times:
50µs for detecting short range objects and 2ms doing the same for the long range.

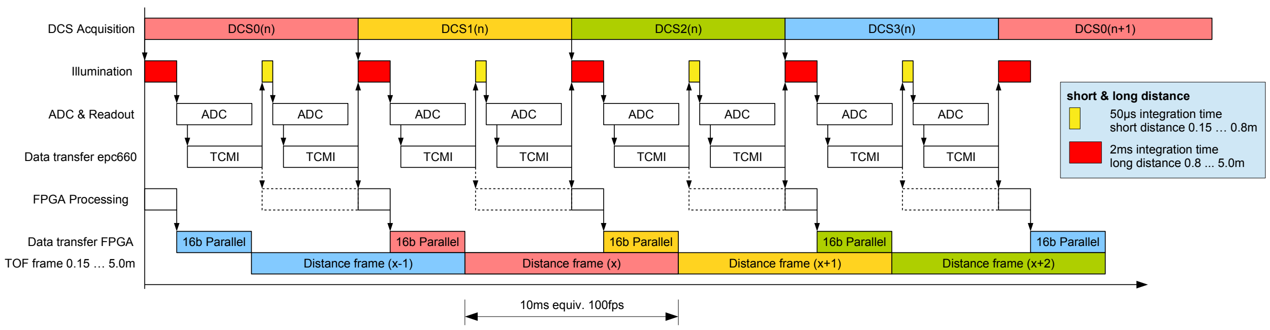


Figure 57: Enhanced rolling mode sequence

Implementation example step by step: Rolling mode using 3 integration times

1. Chose single frame mode by setting register 0x22 and 0x92.
2. Run 4 DCS turns by
3. Select DCS0 and acquire 3 DCS0 each with one of the 3 integration times
   Integration time t1 > shutter > readout > integration time t2 > shutter > readout > integration time t3 > shutter > readout.
   2nd and following turns:
   Calculate for each integration time the distance and TOF amplitude image with the last 4 corresponding DCS frames.
   Select out of the acquired integration time distance images, already compensated, each time the most reliable distance information and compose the actual final distance picture.
4. Select DCS1 and acquire 3 DCS1each with one of the 3 integration times
   Integration time t1 > shutter > readout > integration time t2 > shutter > readout > integration time t3 > shutter > readout
   2nd and following turns:
   Calculate for each integration time the distance and TOF amplitude image with the last 4 corresponding DCS frames.

Select out of the acquired integration time distance images, already compensated, each time the most reliable distance information and compose the actual final distance picture.

… and so on ...

<table>
<tr><th></th><th>Register</th><th>0x22</th><th>0x25</th><th>0x92</th></tr>
<tr><th>Mode</th><th>DCS/Shutter</th><th>DCS select
1st frame</th><th>DCS select
2nd frame</th><th>Modulation select</th></tr>
<tr><td>4 DCS</td><td>DCS 0, 1, 2, 3</td><td>0x34</td><td>0x3D</td><td>0x30</td></tr>
<tr><td rowspan="2">2 DCS</td><td>DCS 0, 1</td><td>0x34</td><td>0x3D</td><td rowspan="2">0x10</td></tr>
<tr><td>DCS 2, 3</td><td>0x32</td><td>0x33</td></tr>
<tr><td rowspan="4">1 DCS rolling</td><td>DCS 0</td><td>0x34</td><td rowspan="4">Not used</td><td rowspan="4">0x00</td></tr>
<tr><td>DCS 1</td><td>0x31</td></tr>
<tr><td>DCS 2</td><td>0x32</td></tr>
<tr><td>DCS 3</td><td>0x33</td></tr>
</table>

Table 32: DCS selection for enhanced rolling mode

12. Parameter and configuration memory

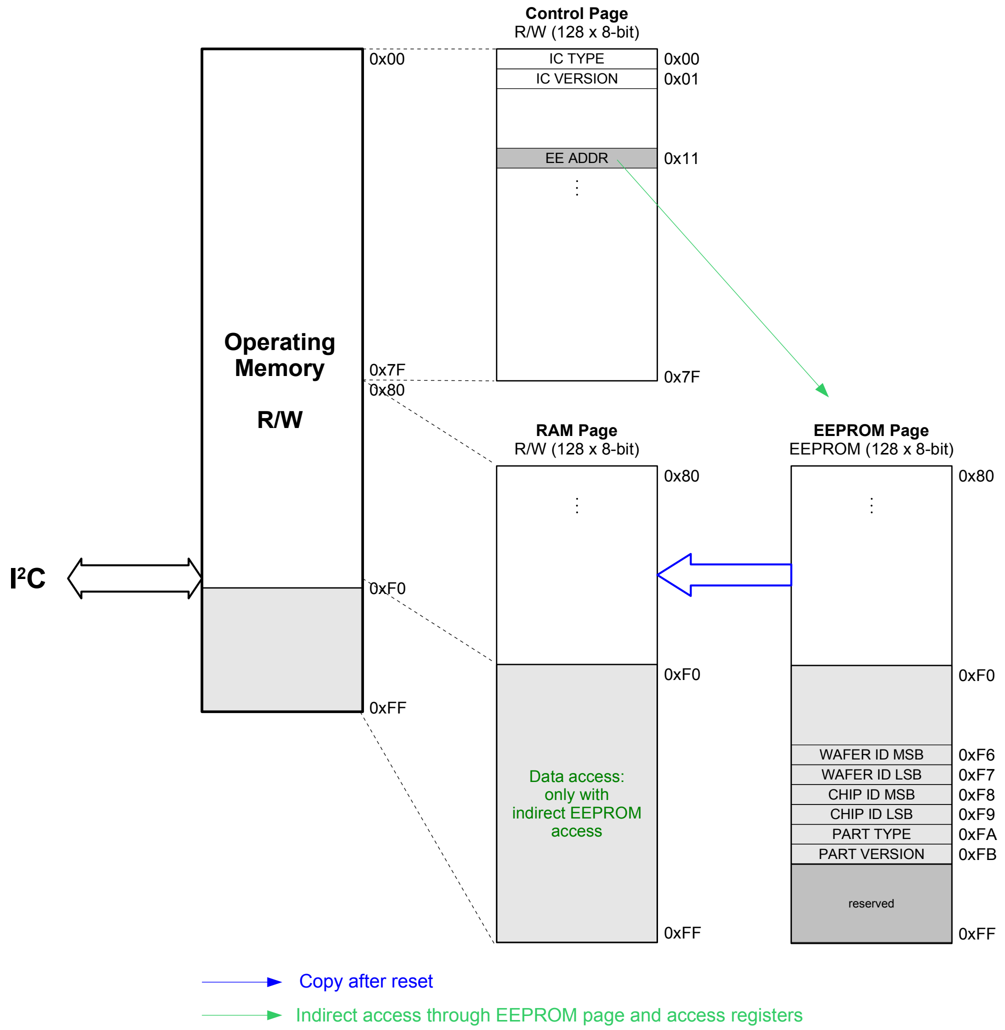


Figure 58: Memory map

12.1. Data memory map

The epc660 control registers (RAM) are used for controlling all features of the chip. They are organized as 256x8 bit into 0x00 ... 0xFF address locations. The address space 0x80 ... 0xFF is EEPROM backed-up. EEPROM parameters in this section are stored permanently between the power off/on cycles. All registers can be accessed through I²C interface by the application CPU (see chapter 13, I2C interface). Multiple byte registers are stored in the order MSB first, then LSB.

12.1.1. Control page

The control page contains R/W accessible registers with default values during startup. The content can be changed via the I²C interface. The changed values are preserved as long as the IC is powered. They are set back to their default values with a reset.

12.1.2. RAM page

The RAM page contains R/W accessible registers with EEPROM copied values after startup. The content can be changed via the I²C interface. The changed values are preserved as long as the IC is powered. They are set back to EEPROM values with a reset.

12.1.3. EEPROM page

The embedded 128x8-bit EEPROM stores operation parameters as well as factory set trimming and calibration values.

13. I²C interface

The I²C-bus interface allows accessing the RW registers and the programming of the EEPROM registers which store the configuration parameters. It is the only interface through which the configuration registers can be accessed (Figure 58 and Table 35) by the application. It works as a slave device according to the I²C specification (refer to chapter 16.2) with a transfer rate of up to 400 kbit/s in Fast Mode (FM) or 1Mbit/s in Fast Mode plus (FM+). The I²C master such as an external CPU can set the transfer speed simply by driving the SCL input at that frequency (up to 1MHz), therefore there is no prior register configuration or setting necessary.

I²C specification is supported in epc660 with following remarks/exceptions:

- 7-bit addressing only is supported.
- Clock stretching is supported.
- General call address: By transmitting 0x00 followed by 0x06 (issues software reset) or transmitting 0x00 followed by 0x04 (device address reload), the programmable part (A0, A1) of the I²C address pins is overwritten by the initially scanned value through strap pins during start-up or reset phase.
- Software reset is supported.
- Other uses of I²C bus are not supported.

13.1. Device addressing

The epc660 7-bit I²C device address is hard-wired to the value shown below in Figure 59. Two address bits A0, A1 can be optionally initialized as 1 through strap pins (chapter 5.6.3). In a typical single-camera 3D TOF imager application in which epc660 is directly connected as a single I²C slave to a single I²C master, the strap pins can be can be left open. An internal pull down resistor keeps them low. In this case, the device address is set after reset default as 0100000. In a multi-camera application with up to 4 epc660 devices connected on the same I²C bus as slaves or together with other I²C slaves talking to a single I²C master, external pull-up resistors can be utilized on the strap pins to initialize different I²C device addresses in order to correctly identify different epc660 slaves on the bus.

MSB							LSB
0	1	0	0	0	A1	A0	**R/$\overline{\text{W}}$**

Figure 59: Device address through I²C

13.2. I²C bus protocol notation

The following notation is used:

- S **S**TART condition
- P STO**P** condition
- A **A**cknowledge last byte (ACK)
- $\overline{\text{A}}$ **N**ot-Acknowledge last byte (NACK)
- Shaded part of protocol: transmitted by master
- Unshaded part of protocol: transmitted by epc660

13.3. I²C bus timing

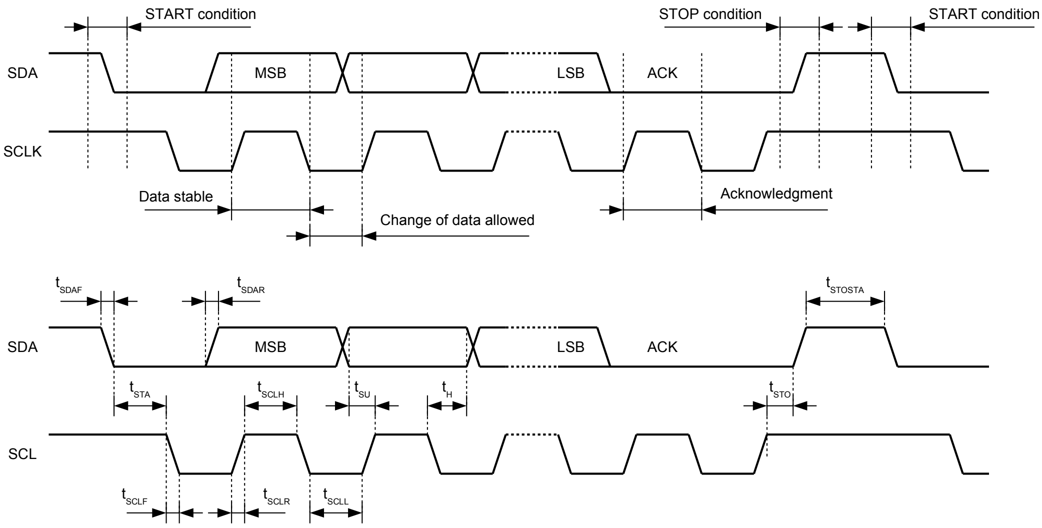


Figure 60: I²C bus timing

Symbol	Parameter	Min.	Max.	Units
t_{SCLL}	SCL clock low time	0.5		µs
t_{SCLH}	SCL clock high time	0.26		µs
t_{SU}	SDA setup time	50		ns

t_H	SDA hold time		0	ns
t_{SDAR} / t_{SCLR}	SDA and SCL rise time		120	ns
t_{SDAF} / t_{SCLF}	SDA and SCL fall time		120	ns
t_{STA}	Start condition hold time	0.26		µs
t_{STO}	Stop condition setup time	0.26		µs
t_{STOSTA}	Stop to start condition time (bus free)	0.5		µs
C_b	Capacitive load for each bus line		550	pF
t_{SP}	Pulse width of the spikes that are suppressed by the analog filter		50	ns

Table 33: I²C bus timing: Timing parameters (FM+)

13.4. I²C commands

13.4.1. Software reset

(0x00, 0x06) issues a software reset, same behavior like hardware reset.

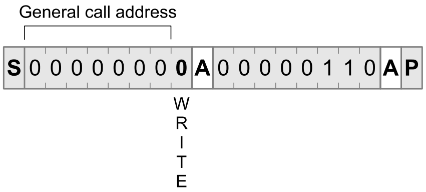


Figure 61: Software reset through I²C

13.4.2. Device address reload

(0x00, 0x04) activates the I²C address stored in register 0xCA. Note that the the values of A0 and A1 cannot be changed by software. Therefore, this general call command only works for bits 2 to 6 of register 0xCA (chapter 5.6.3).

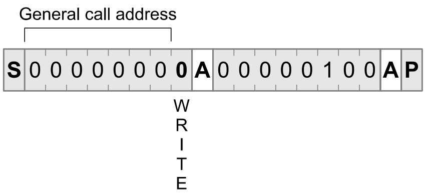


Figure 62: Device address A1, A0 reload through I²C

13.4.3. Write single-byte

During a single-byte write, only one register is written. After the device address is transmitted, the master has to transmit the register address and the write data in two I²C data packets (Figure 63). The access is terminated by a STOP condition.

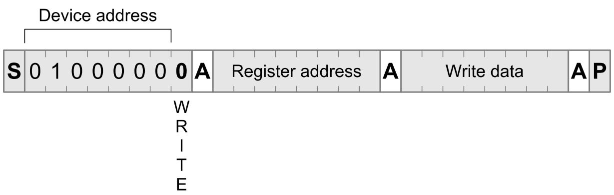


Figure 63: Single-byte Write access through I²C

13.4.4. Write multi-byte

During a multi-byte write operation, the master transmits the device address and the address of the first register to be written. All subsequent bytes until the STOP condition are interpreted as write data packets (Figure 64). The write address pointer is incremented internally. Do not transmit more bytes that the write address pointer reaches the limit of the address space (see chapter 14, Table 35 andTable 36).

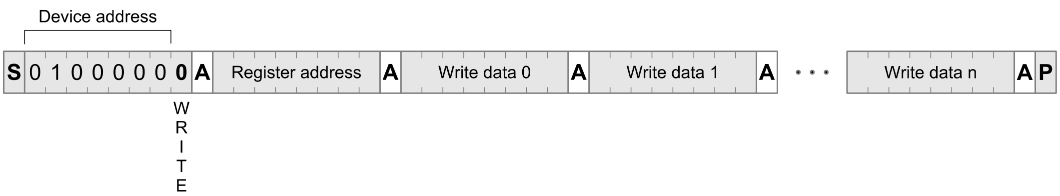


Figure 64: Multi-byte Write access through I²C

13.4.5. Read single-byte

The master transmits first the device address with a write command. Next, it writes the register address to be read. Then, the master transmits the device address again with a read command where the epc660 answers with the data stored in the addressed register. Finally, the master terminates the read sequence with a NACK and a STOP (Figure 65).

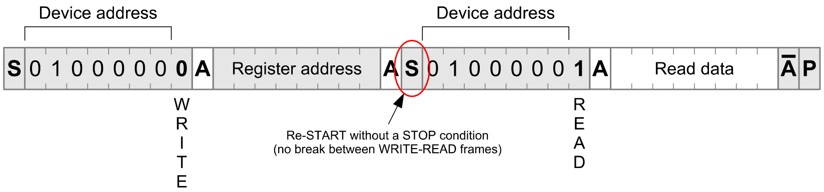


Figure 65: Single-byte Read access through I²C

13.4.6. Read multi-byte

The master transmits first the device address and the address of the first register to be read. After the epc660 is addressed with a read command, epc660 answers with read data bytes until the master does not acknowledge a byte. The master is expected to terminate the access with a STOP condition thereafter (Figure 66). During the access the read address pointer is incremented epc660 internally. Do not transmit more bytes that the write address pointer reaches the limit of the address space (see chapter 14, Table 35 andTable 36).

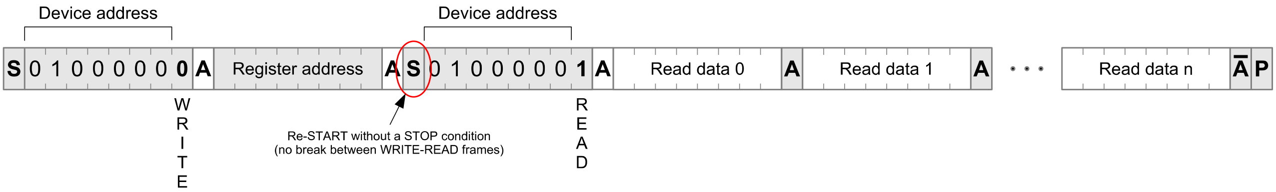


Figure 66: Multi-byte Read access through I²C

13.5. Command timing

The operating modes of the epc660 are initialized, activated, deactivated and monitored by sending several single or multi-byte write and read command sequences through I²C interface. This section lists and explains available commands together with their access time (f_{SCL} = 1MHz → t_{SCL} = 1µs).

There is no particular order defined for sending the commands. The only requirement is having no on-going frame acquisition process when updating non-shadowed registers. The registers marked with ** in the register map can be updated on-the-fly during a frame acquisition. New values are used by the next frame.

Command	**Description**	**Length [Bytes]**	**Time [µs]**
Single-byte Write	Single-byte write to control registers	3	29
Multiple-byte Write	Multiple-byte write (n bytes) to control registers	2 + n	20 + n x 9
Single-byte Read	Single-byte read from control registers	4	39
Multiple-byte Read	Multiple-byte read (n bytes) from control registers	3 + n	30 + n x 9
Mode set	4, 2, or 1 DCS set using register 0x92	3	29
Integration time (short) set	Integration time set (up to 800µs) using integration length 1 register	4	38
Integration time (long) set	Integration time set using integration time multiplier and length 1 registers	6	56
Dual Integration time (long) set	Dual int. time set using integration time multiplier and length 1, 2 registers	8	74
Binning, resolution reduction set	Binning and row reduction set using register 0x94	3	29
ROI set	Region of interest set using registers 0x96 – 0x9B.	8	74
Shutter	Start frame acquisition by using the shutter control register	3	29
Integration time (short) + Shutter	Integration time + soft shutter in one go! (Integration length 1 registers, shutter control register)	5	47
EEPROM Indirect Single Write	Indirect single write to EEPROM	9	20ms
EEPROM Indirect Single Read	Indirect single read from EEPROM	10	97

Table 34: I²C Control commands summary

14. Register map

Notes:

** Shadow registers can be updated on-the-fly while a frame acquisition is going on. The new values are used at the start of the next frame.

Not listed registers are reserved and must not be altered by the user. Otherwise, chip malfunction can occur. However, if a register is accidentally overwritten, a RESET restores the factory settings.

The listed default values are after downloading the latest sequencer program to the chip.

14.1. Control page 0x00 ~ 0x7F

<table>
<tr><th>Addr.</th><th>Type</th><th>Default</th><th>Description</th></tr>
<tr><td>0x00</td><td>R</td><td>---</td><td>IC type for device family identification. For chip type refer to register 0xFA.</td></tr>
<tr><td>0x01</td><td>R</td><td>---</td><td>IC version for device mask identification. For chip version refer to register 0xFB.</td></tr>
<tr><td>0x11</td><td>R/W</td><td>---</td><td>Address register for indirect read/write access to EEPROM (refer to 15.6 and 15.7)</td></tr>
<tr><td>0x12</td><td>R/W</td><td>---</td><td>Data register for indirect read/write access to EEPROM (refer to 15.6 and 15.7)</td></tr>
<tr><td>0x20</td><td>R</td><td>0x00</td><td>Strap scan register. Refer to 5.6.3.
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0..4</td><td>reserved</td><td>0</td></tr>
<tr><td>5</td><td>Strap input 0: I²C address A0</td><td>0</td></tr>
<tr><td>6</td><td>Strap input 1: I²C address A1</td><td>0</td></tr>
<tr><td>7</td><td>reserved</td><td>0</td></tr>
</table>
Default start-up values of these registers are only valid until end of reset phase. Values might be over-written by external pull-up resistors during strap scan phase when reset is released.</td></tr>
<tr><td>0x22</td><td>R/W</td><td>0x30</td><td>DCS and ABS selection for 1st frame. Refer to chapter 8
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td rowspan="2">DCS number for mgx0 modulator (mga0, mgb0), all modes
00: DCS 0
01: DCS 1
10: DCS 2
11: DCS 3</td><td>0</td></tr>
<tr><td>1</td><td>0</td></tr>
<tr><td>2</td><td rowspan="2">DCS number for mgx1 modulator (mga1, mgb1), dual modes only
00: DCS 0
01: DCS 1
10: DCS 2
11: DCS 3</td><td>0</td></tr>
<tr><td>3</td><td>0</td></tr>
<tr><td>4</td><td rowspan="2">Extended background suppression ABS. Refer to chapter 1.6 and 7.2.
00: ABS disabled, Saturation detection not active
01: reserved
10: reserved
11: ABS enabled (default). Refer to Table 6</td><td>1</td></tr>
<tr><td>5</td><td>1</td></tr>
<tr><td>6, 7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
<tr><td>0x24</td><td>R/W</td><td>0x00</td><td>Modulation control 1st frame. Refer to chapter 8
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0..3</td><td>reserved</td><td>0</td></tr>
<tr><td></td><td rowspan="2">0: LED/LD is modulated
1: LED/LD on during integration: Refer to IMPORTANT NOTE chapter 5.7</td><td>0</td></tr>
<tr><td></td><td>0</td></tr>
<tr><td></td><td rowspan="2">0: LED/LD is modulated
1: LED/LD off during integration</td><td>0</td></tr>
<tr><td></td><td>0</td></tr>
<tr><td>6, 7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
<tr><td>0x25</td><td>R/W</td><td>0x35</td><td>DCS and ABS selection for 2nd frame. Description see register 0x22.</td></tr>
<tr><td>0x27</td><td>R/W</td><td>0x00</td><td>Modulation control 2nd frame. Description see register 0x24.</td></tr>
<tr><td>0x28</td><td>R/W</td><td>0x3A</td><td>DCS and ABS selection for 3rd frame. Description see register 0x22.</td></tr>
<tr><td>0x2A</td><td>R/W</td><td>0x00</td><td>Modulation control 3rd frame. Description see register 0x24.</td></tr>
<tr><td>0x2B</td><td>R/W</td><td>0x3F</td><td>DCS and ABS selection for 4th frame. Description see register 0x22.</td></tr>
<tr><td>0x2D</td><td>R/W</td><td>0x00</td><td>Modulation control 4th frame. Description see register 0x24.</td></tr>
<tr><td>0x3A</td><td>R/W</td><td>0x10</td><td>Readout mode for grayscale
0x00: differential readout. Select this mode by the user application, refer to chapter 9.3 and 10.1
0x10: single-ended readout (negative numbers are clipped)
0x30: differential readout with ABS (recommended)</td></tr>
<tr><td>0x3C</td><td>R/W</td><td>0x26</td><td>Modulation control in grayscale mode. Refer to chapter 9.3 and Table Table 27.
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td>reserved</td><td>0</td></tr>
<tr><td>1..2</td><td>reserved</td><td>1</td></tr>
<tr><td>3</td><td>reserved</td><td>0</td></tr>
<tr><td>4</td><td>0: LED/LD modulated
1: LED/LD on during integration</td><td>0</td></tr>
<tr><td>5</td><td>0: LED/LD modulated
1: LED/LD off during integration</td><td>1</td></tr>
<tr><td>6..7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
</table>

Table 35: Address map of the control page (0x00 ~ 0x7F)

Addr.	Type	Default	Description
0x60	R	---	Temperature sensor top left, refer to chapter 10. Sum of 4 consecutive readings of the temperature sensor every 4th row reading
0x61	R	---	
0x62	R	---	Temperature sensor top right. Description see register 0x60.
0x63	R	---	
0x64	R	---	Temperature sensor bottom left. Description see register 0x60.
0x65	R	---	
0x66	R	---	Temperature sensor bottom right Description see register 0x60.
0x67	R	---	
0x71	R/W	0x00	Number of fine DLL delay steps to delay the LED output by approx. 10ps per step. Max. value is 799 (0x31F). Valid only if bit 2 in register 0xAE is enabled. Refer also to register 0xAE and chapter 5.8. Note: Delay is sensitive to VDD variations and noise.
0x72	R/W	0x00	
0x73	R/W	0x00	Number of coarse DLL delay steps to delay the LED output by approx. 2ns per step. Max. value is 49 (0x31). Valid only if bit 2 in register 0xAE is enabled. Refer also to register 0xAE and chapter 5.8. Note: Delay is sensitive to VDD variations and noise.
0x7D	R/W	0x04	Mode control <table><tr><th>Bit</th><th>Function</th><th>Default</th></tr><tr><td>0..1</td><td>reserved</td><td>0</td></tr><tr><td>2</td><td>Enable PLL 0: disable 1: enable</td><td>1</td></tr><tr><td>3..7</td><td>reserved</td><td>0</td></tr></table>

Cont. Table 35: Address map of the control page (0x00 ~ 0x7F)

14.2. RAM page (0x80 ~ 0xEF)

Addr.	Type	Default	Description
0x80	R/W	0x3F	Clock control <table><tr><th>Bit</th><th>Function</th><th>Default</th></tr><tr><td>0..5</td><td>reserved</td><td>1</td></tr><tr><td>6</td><td>Modulation clock source 0: Internal modulation clock 1: External clock from MODCLK input</td><td>0</td></tr><tr><td>7</td><td>reserved</td><td>0</td></tr></table>
0x85	R/W	0x01	Modulation clock divider <table><tr><th>Bit</th><th>Function</th><th>Default</th></tr><tr><td>0</td><td rowspan="5">Modulation clock divider provides clock to the LED/Pixel-field modulator/demodulator circuits by integer division of the internal PLL clock or external MODCLK: f_{mod_clk} = 96MHz / (modulation clock divider + 1) Default: 96MHz / (0x01 + 0x01): f_{mod_clk} = 48MHz Maximal value of modulation clock divider = 0x1F: f_{mod_clk} = 3.0MHz Note: The LED modulation frequency is 4 times lower than f_{mod_clk}</td><td>1</td></tr><tr><td>1</td><td>0</td></tr><tr><td>2</td><td>0</td></tr><tr><td>3</td><td>0</td></tr><tr><td>4</td><td>0</td></tr><tr><td>5..7</td><td>reserved</td><td>0</td></tr></table>

Table 36: Address map of RAM page (0x80 ~ 0xEF)

<table>
<tr><th>Addr.</th><th>Type</th><th>Default</th><th>Description</th></tr>
<tr><td>0x89</td><td>R/W</td><td>0x03</td><td>TCMI clock control
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td rowspan="5">TCMI clock divider:
f_{tcmi_clk} = 96MHz / (TCMI clock divider + 1)
Default: 96MHz / (0x03 + 0x01) = 24MHz
Minimal value of TCMI clock divider = 0x01 = 48.0MHz
Maximal value of TCMI clock divider = 0x1F = 3.0MHz
Important: Regarding readout rollover, refer to Figure 30 and register 0x91 regarding DCLK stretch</td><td>1</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td>2</td><td>0</td></tr>
<tr><td>3</td><td>0</td></tr>
<tr><td>4</td><td>0</td></tr>
<tr><td>5..6</td><td>reserved</td><td>0</td></tr>
<tr><td>7</td><td>DCLK skew enable:
0: disable
1: enable
Used to delay DCLK edge (typ. 2ns) to compensate PCB delays.
Might be particularly useful when TCMI clock divider = 0 (divided by 1).
When set normal, DCLK edge is centred with respect to other TCMI *SYNC*, DATA[11:0] outputs.</td><td>0</td></tr>
</table></td></tr>
<tr><td>0x8B</td><td>R/W</td><td>0x01</td><td>Number of PLL clock periods delay of the demodulation signal path (all modulation modes). It can be used to insert a phase shift between modulation (LED) and demodulation (pixel). 1 PLL clock cycle is around 10.4ns @ 96MHz PLL clock. This is equivalent to a distance shift of 1.5625m independent of the LED modulation frequency. Note: This phase shift is temperature independent.
0: no delay
1: 1 clock
2: 2 clocks
…
12: 12 clocks (max. value)</td></tr>
<tr><td>0x90</td><td>R/W</td><td>0xC4</td><td>LED driver control. Refer to chapter 5.3 and 5.7.
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td>reserved</td><td>0</td></tr>
<tr><td>1</td><td>Inverts output signals LED and LED2 if drivers are enabled
0: not inverted, e.g. LED = 0, not active: Pin LED non-conductive, LED2 = VSSIO.
1: inverted, e.g. LED = 0, not active: Pin LED conductive, LED2 = VDDIO.</td><td>0</td></tr>
<tr><td>2</td><td>LED output select:
0: LED driver is disable. Pin LED is non-conductive.
1: LED driver is enabled.</td><td>1</td></tr>
<tr><td>3</td><td>LED preheat enable
0: disable
1: enable</td><td>0</td></tr>
<tr><td>4</td><td>LED/LD permanently on (torch function, no modulation) if drivers are enabled:
0: off
1: on (Refer to IMPORTANT NOTE chapter 5.7)</td><td>0</td></tr>
<tr><td>5</td><td>LED2 output select:
0: LED2 driver disabled. Output is in Tri-State with termination resistor to VSSIO.
1: LED2 driver enabled.</td><td>0</td></tr>
<tr><td>6..7</td><td>reserved</td><td>1</td></tr>
</table></td></tr>
<tr><td>0x91</td><td>R/W</td><td>0x03</td><td>Sequencer control
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0..1</td><td>reserved</td><td>1</td></tr>
<tr><td>3..5</td><td>reserved</td><td>0</td></tr>
<tr><td>6</td><td>Avoids readout rollover when using slower DCLK < 13MHz and default ROI.
Stretches HSYNC for slower TCMI interface. Causes reduced DCS frame rate due to additional 2µs per ADC conversion (t_{conv} + 2µs). Refer also to register 0x89.
0: disable (default)
1: enable for DCLK < 13MHz and default ROI. Refer to Figure 30 and note above.</td><td>0</td></tr>
<tr><td>7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
</table>

Cont. Table 36: Address map of RAM page (0x80 ~ 0xEF)

<table>
<tr><th>Addr.</th><th>Type</th><th>Default</th><th>Description</th></tr>
<tr><td>0x92**</td><td>R/W</td><td>0x34</td><td>Modulation select
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0..1</td><td>reserved</td><td>0</td></tr>
<tr><td>2</td><td>reserved</td><td>1</td></tr>
<tr><td>3</td><td>Dual integration time mode – acquisition with 2 integration times per DCS frame using additionally integration length 2, registers 0x9E and 0x9F
0: disable
1: enable
Needs register 0x94 set to 0x80, otherwise it is not effective (see Figure 43)</td><td>0</td></tr>
<tr><td>4</td><td rowspan="2">Number of DCS readouts select:
00: Grayscale mode, DCS0 only
01: Dual phase mode, DCS0, DCS1 or DCS2,DCS3
10: reserved
11: Full resolution mode or dual int. mode, DCS0, DCS1, DCS2, DCS3</td><td>1</td></tr>
<tr><td>5</td><td>1</td></tr>
<tr><td>6</td><td rowspan="2">Modulation select:
00: TOF mode
01: reserved
10: reserved
11: Grayscale mode</td><td>0</td></tr>
<tr><td>7</td><td>0</td></tr>
</table>
</td></tr>
<tr><td>0x94**</td><td>R/W</td><td>0x00</td><td>Resolution reduction, binning and pixel-field mode
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td rowspan="2">Column reduction: resolution on x-axis. Refer to chapter 8.5.
00: no (0, 1, 2, …)
01: by half (0, 2, 4, …)
10 & 11: reserved</td><td>0</td></tr>
<tr><td>1</td><td>0</td></tr>
<tr><td>2</td><td rowspan="2">Row reduction: resolution on y-axis. Refer to chapter 8.5
00: no (0, 1, 2, …)
01: by half (0, 2, 4, …)
10: a quarter (0, 4, 8, …)
11: one eight (0, 8, 16, …)</td><td>0</td></tr>
<tr><td>3</td><td>0</td></tr>
<tr><td>4</td><td rowspan="2">Pixel binning. Refer to chapter 8.4.
00: no binning
01: binning x-axis if bit 0, 1 <> 00
10: binning y-axis if bit 2, 3 <> 00
11: binning x and y-axis if bit 0, 1 <> 00 AND bit 2, 3 <> 00
Notes:
- Choose corresponding row and/or column reduction to binning selection.
- Binning cannot be used with dual phase and dual integration time mode.</td><td>0</td></tr>
<tr><td>5</td><td>0</td></tr>
<tr><td>6</td><td>reserved</td><td>0</td></tr>
<tr><td>7</td><td>Select pixel-field mode (refer to chapter 8.1, 8.2, 8.3)
0: Standard TOF mode: full resolution
1: Dual modes: dual phase and dual integration time</td><td>0</td></tr>
</table>
</td></tr>
<tr><td>0x96**</td><td>R/W</td><td>0x00</td><td rowspan="2">ROI top left X setting. Refer to chapter 8.6.</td></tr>
<tr><td>0x97**</td><td>R/W</td><td>0x04</td></tr>
<tr><td>0x98**</td><td>R/W</td><td>0x01</td><td rowspan="2">ROI bottom right X setting.</td></tr>
<tr><td>0x99**</td><td>R/W</td><td>0x43</td></tr>
<tr><td>0x9A**</td><td>R/W</td><td>0x06</td><td>ROI top left Y setting.</td></tr>
<tr><td>0x9B**</td><td>R/W</td><td>0x7D</td><td>ROI bottom right Y setting.</td></tr>
<tr><td>0x9E**</td><td>R/W</td><td>0x07</td><td rowspan="2">Integration length 2: Number of modulation clock periods for the second integration time in the dual integration time mode (refer to 8.3, default: 2'047). See registers 0xA2 and 0xA3 for functional definition details.
Bit 3 in register 0x92 has to be set to 1 to enable this integration time for the even rows. The odd rows operate with the integration length 1 set in registers 0xA2 and 0xA3.</td></tr>
<tr><td>0x9F**</td><td>R/W</td><td>0xFF</td></tr>
<tr><td>0xA0**</td><td>R/W</td><td>0x00</td><td rowspan="2">Integration time multiplier (10 bit value) for integration lengths set with the integration length registers (default = 1, min. value = 1). This multiplier is active on both settings integration length 1 and 2.</td></tr>
<tr><td>0xA1**</td><td>R/W</td><td>0x01</td></tr>
<tr><td>0xA2**</td><td>R/W</td><td>0x07</td><td rowspan="2">Integration length 1: Number of modulation clock periods for the (first in dual integration time mode) integration time (16 bit value, default = 2'047, min. value = 7 which is integration time 167ns @ 12MHz).
Integration time = Integration time multiplier * (Integration length +1) * t_{mod_clk}
e.g. for defaults @ 12MHz modulation clock = 42.6µs
Note: (Integration length + 1) should be evenly divisible by 4.</td></tr>
<tr><td>0xA3**</td><td>R/W</td><td>0xFF</td></tr>
</table>

Cont. Table 36: Address map of RAM page (0x80 ~ 0xEF)

<table>
<tr><th>Addr.</th><th>Type</th><th>Default</th><th>Description</th></tr>
<tr><td>0xA4</td><td>R/W</td><td>0x00</td><td>Shutter Control
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td>Shutter release. Refer to chapter 6.2.
0: disable
1: enable. In single shot mode: Starts acquisition and is auto cleared.
Note: Shutter release is not auto-cleared when multiple frames is enable.</td><td>0</td></tr>
<tr><td>1</td><td>Multiple frames (auto-run or video mode). Refer to chapter 6.2.
0: disable. Single shot mode.
1: enable. Multiple frame mode active if shutter enabled. Refer to chapter 6.2.2.</td><td>0</td></tr>
<tr><td>2..7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
<tr><td>0xA5</td><td>R/W</td><td>0x07</td><td>Power control. Refer to chapter 11.5.
0x00: Power off
0x07: Power on</td></tr>
<tr><td>0xAB</td><td>R/W</td><td>0x04</td><td>Only valid configurations (in combination with register 0x90):

LED preheat enabled: 0x90, bit 3 = 1 and 0xAB = 0x01 (recommended configuration)
LED preheat disabled: 0x90, bit 3 = 0 and 0xAB = 0x00</td></tr>
<tr><td>0xAE</td><td>R/W</td><td>0x01</td><td>DLL control (Refer also to register 0x73 and chapter 5.8)
0x01: no delay
0x04: delay manually set by register 0x73
Note: The change of register 0xAE from 0x01 to 0x04 generates also a delay, even if register 0x73 is set to 0x00.</td></tr>
<tr><td>0xAF</td><td>R/W</td><td>0x0D</td><td>Saturation threshold (factory setting, do not change)</td></tr>
<tr><td>0xCA</td><td>R/W</td><td>0x20</td><td>I^{2}C addressing
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td rowspan="2">reserved, I^{2}C address A1, A0 of 7-bit I^{2}C device address. Programmable only during reset via strap pins using external pull-up resistors.</td><td>0</td></tr>
<tr><td>1</td><td>0</td></tr>
<tr><td>2</td><td rowspan="5">I^{2}C device address A6 … A2 of 7-bit I^{2}C device address.
Programmable via direct access from I^{2}C or from EEPROM during start up, followed by an I^{2}C general call “Device address reload” to take it into effect.</td><td>0</td></tr>
<tr><td>3</td><td>0</td></tr>
<tr><td>4</td><td>0</td></tr>
<tr><td>5</td><td>1</td></tr>
<tr><td>6</td><td>0</td></tr>
<tr><td>7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
<tr><td>0xCB</td><td>R/W</td><td>0x03</td><td>I^{2}C and TCMI control. Refer to chapter 13 and 6.4.
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td>I^{2}C clock stretching
0: disabled
1: enabled</td><td>1</td></tr>
<tr><td>1</td><td>I^{2}C pins input spike filter
0: disabled (> 1MHz)
1: enabled (≤ 1MHz, FM+)
When I^{2}C pins input spike filter = 0, SDA and SCL pins can be used up to 10MHz as inputs (driven rail-to-rail by a real CMOS driver, no pull-up) and up to 2MHz as outputs.</td><td>1</td></tr>
<tr><td>2, 3</td><td>reserved</td><td>0</td></tr>
<tr><td>4</td><td rowspan="2">00: Transfers 12 bit pixel data with 1x DCLK (default).
01: Transfers the 8 MSB bits of the pixel data with 1x DCLK. Data are LSB aligned.
10: lsb/msb split mode: Transfers 12 bit pixel data with LSByte leading and MSByte trailing with 2x DCLK. Data are LSB aligned (default). The optional SAT bit is on the LSB.
11: msb/lsb split mode: Transfers 12 bit pixel data with MSByte leading and LSByte trailing with 2x DCLK. Data are LSB aligned. The optional SAT bit is on the LSB.</td><td>0</td></tr>
<tr><td>5</td><td>0</td></tr>
<tr><td>6</td><td>When split modes selected (= 11 or 10), forces bit DATA[0] of the LSByte = 1 when the pixel is saturated. Not effective with other TCMI data formats.
0: disabled
1: enabled</td><td>0</td></tr>
<tr><td>7</td><td>reserved</td><td>0</td></tr>
</table></td></tr>
</table>

Cont. Table 36: Address map of RAM page (0x80 ~ 0xEF)

<table>
<tr><th>Addr.</th><th>Type</th><th>Default</th><th>Description</th></tr>
<tr><td>0xCC</td><td>R/W</td><td>0x41</td><td>TCMI polarity settings. Refer to chapter 6.4.
<table>
<tr><th>Bit</th><th>Function</th><th>Default</th></tr>
<tr><td>0</td><td>DCLK edge select to align all other TCMI outputs
0: falling edge
1: rising edge</td><td>1</td></tr>
<tr><td>1</td><td>HSYNC polarity
0: HSYNC active low
1: HSYNC active high</td><td>0</td></tr>
<tr><td>2</td><td>VSYNC polarity
0: VSYNC active low
1: VSYNC active high</td><td>0</td></tr>
<tr><td>3</td><td>XSYNC polarity
0: XSYNC active low
1: XSYNC active high
Only effective when bit 6 is set to 0</td><td>0</td></tr>
<tr><td>4</td><td>DATA[11:0] unsigned/signed TCMI data output format
0: unsigned integer, subtract 2'048 to get correct value (Default)
1: two's complement signed integer (-2'048 ... 2'047)</td><td>0</td></tr>
<tr><td>5</td><td>reserved</td><td>0</td></tr>
<tr><td>6</td><td>Select XSYNC / SAT output pin function
0: XSYNC
1: SAT</td><td>1</td></tr>
<tr><td>7</td><td>Force DATA[11:0] = 0xFFF (unsigned) / 0x7FF (signed, two's complement) during data-out operation when corresponding pixel is saturated
0: disabled
1: enabled</td><td>0</td></tr>
</table></td></tr>
<tr><td>0xE8</td><td>R/W</td><td>---</td><td>Temperature offset correction for sensor top left. Value for calculation according the formula in chapter 10 by the application SW. Range approx. -27 … +27ºC with around 0.2ºC steps. The reference temperature is +27ºC. 0x7F (127) corresponds to 0ºC offset. 0xFF: Function is not supported.</td></tr>
<tr><td>0xAE0x-AE0xE9</td><td>R/W</td><td>---</td><td>DLL step. Supported for Wafer IDs 212 or higher. Refer for details to register 0x73 and Figure 23.
The exact value is t_{DLL} = ((register 0xE9 -128) * 0.003ns) + 2.1ns (at +27ºC, V_{DD},V_{DDPLL} = 1.8V).
0xFF: Function is not supported.</td></tr>
<tr><td>0xEA</td><td>R/W</td><td>---</td><td>Temperature offset correction for sensor top right. Description see register 0xE8.</td></tr>
<tr><td>0xEC</td><td>R/W</td><td>---</td><td>Temperature offset correction for sensor bottom left. Description see register 0xE8.</td></tr>
<tr><td>0xEE</td><td>R/W</td><td>---</td><td>Temperature offset correction for sensor bottom right. Description see register 0xE8.</td></tr>
</table>

Cont. Table 36: Address map of RAM page (0x80 ~ 0xEF)

14.3. EEPROM page, indirect data access section (0xF0 ~ 0xFF)

Addr.	Type	Default	Description
0xF0	R/W	0x00	User register for user data. Do not write the register during frame acquisition. The number of WRITE cycles into the EEPROM should not exceed 100 WRITE operations.
0xF5	R	0x00	Customer ID
0xF6	R	---	Wafer ID
0xF7	R	---	
0xF8	R	---	Chip ID
0xF9	R	---	
0xFA	R	0x02	Chip and part type: 0x02 = epc660
0xFB	R	---	Chip and part version (release) e.g. 0x07 for version -007, 0x0B for version -011

Table 37: Address map of EEPROM page (0xF0 ~ 0xFF)

15. Control command examples

15.1. I²C control command examples:

To simplify command sequence definitions, following C-programming language style functions are defined for the I²C master CPU:

- i2cGeneralCall(byte genAdr, byte cmd); // 20 x t_{SCL} = 20µs
- i2cSingleWrite(byte devAdr, byte regAdr, byte regVal); // 29 x t_{SCL} = 29µs
- i2cMultiWrite(byte devAdr, byte regAdr, byte* regVal, byte n // 20 + (n x 9 x t_{SCL}) = 20 + (n x 9)µs
- byte i2cSingleRead(byte devAdr, byte regAdr); // 39 x t_{SCL} = 39µs
- byte* i2cMultiRead(byte devAdr, byte regAdr, byte n); // 30 + (n x 9 x t_{SCL}) = 30+(n x 9)µs

15.2. Software reset with I²C general call command

PRECONDITION: None

1. i2cGeneralCall(0x00, 0x06); // Software reset, same effect like $\overline{RESET}$ pin, 20µs
2. … // Wait for $t_{\overline{RESET}}$ (> 100ns)

15.3. 4 DCS: Acquire DCS0 … 3 frames with t_{int} = 16.6µs @ 12MHz modulation frequency

PRECONDITION: All other registers contain default values.

1. i2cSingleWrite(0x20, 0x92, 0x34); // Modulation control 0x92 = 0x34 (mod. sel. = 00, No. DCS = 11), 29µs
2. i2cMultiWrite(0x20, 0xA2, &(0x031F), 2); // Integration length 1 0xA2/0xA3 = 0x031F (integration time = 16.6µs), 38µs
3. i2cSingleWrite(0x20, 0xA4, 0x01); // Shutter control 0xA4 = 0x01, (shutter release = 1), 29µs
4. … // Acquisition starts. Wait until all 4x DCS frames are finished.

15.4. 4 DCS: Acquire DCS0 … 3 frames with tint = 16.6µs, followed by DCS 0 … 3 with tint 333µs @ 12MHz mod. frequency

PRECONDITION: All other registers contain default values.

1. i2cSingleWrite(0x20, 0x92, 0x34); // Modulation control 0x92 = 0x34 (mod. sel. = 00, No. DCS = 11), 29µs
2. i2cMultiWrite(0x20, 0xA2, &(0x031F), 2); // Integration length 1 0xA2/0xA3 = 0x031F (integration time = 16.6µs), 38µs
3. i2cSingleWrite(0x20, 0xA4, 0x01); // Shutter control 0xA4 = 0x01, (shutter release = 1), 29µs
4. … // Acquisition starts. Wait until all 4x DCS frames are finished.
5. i2cMultiWrite(0x20, 0xA2, &(0x3E7F), 2); // Integration length 1 0xA2/0xA3 = 0x3E7F (integration time = 333µs), 38µs
6. i2cSingleWrite(0x20, 0xA4, 0x01); // Shutter control 0xA4 = 0x01, (shutter release = 1), 29µs
7. … // Acquisition starts. Wait until all 4x DCS frames are finished.

15.5. 2 DCS: Acquire DCS0 and 1 with t_{int} = 16.6µs @ 12MHz modulation frequency

PRECONDITION: All other registers contain default values.

1. i2cSingleWrite(0x20, 0x92, 0x14); // Modulation control 0x92 = 0x34 (mod. sel. = 00, No. DCS = 11), 29µs
2. i2cMultiWrite(0x20, 0xA2, &(0x031F), 2); // Integration length 1 0xA2/0xA3 = 0x031F (integration time = 16.6µs), 38µs
3. i2cSingleWrite(0x20, 0xA4, 0x01); // Shutter control 0xA4 = 0x01, (shutter release = 1), 29µs
4. … // Acquisition starts. Wait until all 2x DCS frames are finished.

15.6. Indirect single write to EEPROM: Store 1 byte at user register 0xF0

PRECONDITION: None

1. i2cSingleWrite(0x20, 0x11, 0xF0); // EEPROM address register 0x11 = 0xF0, 29µs
2. i2cSingleWrite(0x20, 0x12, 0x22); // EEPROM data register 0x12 = 0x22
   // (user register = 0x22), 29µs + 20ms = ~20ms
3. ...

Note 1: Start address is written in address register 0x11 for indirect read/write access to the EEPROM.
Note 2: Each EEPROM data register write starts erase/programming EEPROM.
Each EEPROM write takes 20ms, then it auto-increments the EEPROM address register 0x11 by 1.
Note 3: Corresponding control register value is not modified. Only EEPROM register is modified.
Note 4: EEPROM content will only be copied to corresponding control register after $\overline{RESET}$.

15.7. Indirect single read from EEPROM: Read 1 byte from user register 0xF0

PRECONDITION: None

1. i2cSingleWrite(0x20, 0x11, 0xF0); // EEPROM address register 0x11 = 0xF0, 29µs
2. cal1 = i2cSingleRead(0x20, 0x12); // user value 1 = EEEPROM data register (user register 1 0xF0), 39µs
3. ...

Note 1: Start address is written in the EEPROM address register 0x11.
Note 2: Corresponding control register value is not modified. Only EEPROM is read.

15.8. Reading part version (register 0xFB)

Since there is no RAM register at address 0xFB, the PART VERSION can only be read directly from the EEPROM.

```
# The syntax of the I2C commands is as follows:
# Reading: i2c r REGISTER_ADDRESS [NUMBER_OF_BYTES]
# Writing: i2c w REGISTER_ADDRESS [DATA1 DATA2 ...]

i2c w 11 FB
i2c r 12 01  # Response: PART VERSION
```

15.9. Reading IC version (register 0x01)

I²C command to read IC version

```
# The syntax of the I2C commands is as follows:
# Reading: i2c r REGISTER_ADDRESS [NUMBER_OF_BYTES]

i2c r 01 01  # Response: IC VERSION
```

15.10. Reading WAFER ID and CHIP ID

It can be necessary for technical support to read the WAFER ID and the CHIP ID. Since there are no RAM register at addresses 0xF6 to 0xF9, the WAFER ID and the CHIP ID can only be read directly from the EEPROM.

```
# The syntax of the I2C commands is as follows:
# Reading: i2c r REGISTER_ADDRESS [NUMBER_OF_BYTES]
# Writing: i2c w REGISTER_ADDRESS [DATA1 DATA2 ...]

i2c w 11 F6
i2c r 12 01  # Response:  WAFER ID MSB
i2c r 12 01  # Response:  WAFER ID LSB
i2c r 12 01  # Response:  CHIP ID MSB
i2c r 12 01  # Response:  CHIP ID LSB
```

15.11. Pixel sequencer code write procedure

1. Startup epc660 chip (power up or reset release).
2. Wait until the chip is in READY state.
3. Write the pixel sequencer code from chapter 15.12 to the memory.

Important Notes:

This procedure has to be executed after every power up or after a chip reset release (refer also to chapter 11.1).

Never modify this code sequence. Otherwise malfunction occurs.

15.12. Pixel sequencer code

```
# Pixel Sequencer Code V14
# The following sequence of I2C commands re-program the sequencer to be on most actual functionality.
#
# The syntax of the I2C commands to the imager is as follows:
# Writing: i2c w REGISTER_ADDRESS [RAM_ADDRESS DATA0 DATA1 DATA2 DATA3 DATA4 DATA5 SR_PROGRAM]

i2c w a4 00
i2c w 91 00
i2c w 47 01
i2c w 40 00 43 10 00 C0 00 00 0D
i2c w 40 01 43 10 00 00 01 00 0D
i2c w 40 02 43 10 00 40 0A 00 0D
i2c w 40 03 43 10 10 02 58 00 0D
i2c w 40 04 43 10 20 01 80 00 0D
i2c w 40 05 43 10 F0 01 B0 00 0D
i2c w 40 06 43 10 00 01 60 00 0D
i2c w 40 07 43 10 C0 00 78 00 0D
i2c w 40 08 43 10 40 00 18 00 0D
i2c w 40 09 43 10 D0 02 40 00 0D
i2c w 40 0A 43 10 10 C0 1E 00 0D
i2c w 40 0B 43 10 00 00 50 00 0D
i2c w 40 0C 43 10 20 00 18 00 0D
i2c w 40 0D 43 10 D0 02 40 00 0D
i2c w 40 0E 43 10 10 C0 1E 00 0D
i2c w 40 0F 43 10 00 00 50 00 0D
i2c w 40 10 43 10 D0 02 40 00 0D
i2c w 40 11 43 10 00 00 50 00 0D
```

```
i2c w 40 12 43 18 40 40 02 00 0D
i2c w 40 13 43 08 02 00 00 00 0D
i2c w 40 14 43 08 00 00 A8 00 0D
i2c w 40 15 43 18 80 07 0C 00 0D
i2c w 40 16 43 08 00 00 00 00 0D
i2c w 40 17 43 08 01 00 00 00 0D
i2c w 40 18 43 08 00 00 A8 00 0D
i2c w 40 19 03 08 30 03 40 00 0D
i2c w 40 1A 03 08 E0 01 60 00 0D
i2c w 40 1B 03 08 10 C0 02 00 0D
i2c w 40 1C 03 08 30 03 40 00 0D
i2c w 40 1D 03 00 00 00 00 00 0D
i2c w 40 1E 03 00 00 00 50 00 0D
i2c w 40 1F 43 10 80 40 02 00 0D
i2c w 40 20 43 10 60 00 50 00 0D
i2c w 40 21 43 18 60 40 02 00 0D
i2c w 40 22 43 18 90 07 0C 00 0D
i2c w 40 23 43 08 01 00 00 00 0D
i2c w 40 24 43 08 00 00 A8 00 0D
i2c w 40 25 03 08 30 03 40 00 0D
i2c w 40 26 03 00 88 00 10 00 0D
i2c w 40 27 03 00 88 3E 0C 00 0D
i2c w 40 28 03 00 08 00 14 00 0D
i2c w 40 29 03 00 80 00 10 00 0D
i2c w 40 2A 03 00 80 3E 0C 00 0D
i2c w 40 2B 03 00 00 00 14 00 0D
i2c w 40 2C 03 00 00 00 50 00 0D
i2c w 40 2D 43 08 02 00 00 00 0D
i2c w 40 2E 43 08 00 00 A8 00 0D
i2c w 40 2F 43 18 00 00 00 00 0D
i2c w 40 30 43 08 01 00 3C 00 0D
i2c w 40 31 43 08 00 00 A8 00 0D
i2c w 40 32 43 08 00 00 14 00 0D
i2c w 40 33 43 08 00 C0 00 00 0D
i2c w 40 34 43 08 00 00 01 00 0D
i2c w 40 35 43 88 00 00 00 00 0D
i2c w 40 36 43 08 30 0A 0C 00 0D
i2c w 40 37 43 28 00 00 00 00 0D
i2c w 40 38 43 08 40 00 0C 00 0D
i2c w 40 39 43 08 C0 03 88 00 0D
i2c w 40 3A 43 08 60 09 48 00 0D
i2c w 40 3B 40 18 00 00 44 00 0D
i2c w 40 3C 43 08 F0 03 8C 00 0D
i2c w 40 3D 43 08 50 08 48 00 0D
i2c w 40 3E 40 18 00 00 44 00 0D
i2c w 40 3F 43 08 20 04 90 00 0D
i2c w 40 40 41 08 60 07 48 00 0D
i2c w 40 41 40 18 00 00 44 00 0D
i2c w 40 42 41 08 40 04 48 00 0D
i2c w 40 43 40 18 00 00 44 00 0D
i2c w 40 44 05 08 00 00 34 00 0D
i2c w 40 45 04 08 50 00 0C 00 0D
i2c w 40 46 84 0A F0 00 0C 00 0D
i2c w 40 47 84 0F 00 00 54 00 0D
i2c w 40 48 85 0E 10 00 0C 00 0D
i2c w 40 49 01 0E D0 00 0C 00 0D
i2c w 40 4A 00 0E 00 00 AC 00 0D
i2c w 40 4B 40 2E 00 00 00 00 0D
i2c w 40 4C 40 08 80 05 9C 00 0D
i2c w 40 4D 40 08 60 00 0C 00 0D
i2c w 40 4E 41 08 00 00 00 00 0D
i2c w 40 4F 09 48 00 00 00 00 0D
i2c w 40 50 08 08 50 00 0C 00 0D
i2c w 40 51 88 0A F0 00 0C 00 0D
i2c w 40 52 88 0F 00 00 54 00 0D
i2c w 40 53 89 0E 10 00 0C 00 0D
i2c w 40 54 01 0E D0 00 0C 00 0D
i2c w 40 55 00 0E 00 00 AC 00 0D
i2c w 40 56 40 2E 00 00 00 00 0D
i2c w 40 57 40 08 F0 06 94 00 0D
i2c w 40 58 40 08 F0 06 94 00 0D
i2c w 40 59 40 08 50 00 0C 00 0D
i2c w 40 5A 41 08 00 00 00 00 0D
i2c w 40 5B 11 48 00 00 00 00 0D
i2c w 40 5C 10 08 50 00 0C 00 0D
i2c w 40 5D 90 0A F0 00 0C 00 0D
i2c w 40 5E 90 0F 00 00 54 00 0D
i2c w 40 5F 91 0E 10 00 0C 00 0D
i2c w 40 60 01 0E D0 00 0C 00 0D
i2c w 40 61 00 0E 00 00 AC 00 0D
```

```
i2c w 40 62 40 2E 00 00 00 00 0D
i2c w 40 63 40 08 F0 06 9C 00 0D
i2c w 40 64 40 08 60 00 0C 00 0D
i2c w 40 65 41 08 00 00 00 00 0D
i2c w 40 66 21 48 00 00 00 00 0D
i2c w 40 67 20 08 50 00 0C 00 0D
i2c w 40 68 A0 0A F0 00 0C 00 0D
i2c w 40 69 A0 0F 00 00 54 00 0D
i2c w 40 6A A1 0E 10 00 0C 00 0D
i2c w 40 6B 01 0E D0 00 0C 00 0D
i2c w 40 6C 00 0E 00 00 AC 00 0D
i2c w 40 6D 40 2E 00 00 00 00 0D
i2c w 40 6E 40 08 00 00 00 00 0D
i2c w 40 6F 40 08 00 C0 03 00 0D
i2c w 40 70 40 08 50 00 0C 00 0D
i2c w 40 71 41 48 00 00 14 00 0D
i2c w 40 72 00 08 00 00 54 00 0D
i2c w 40 73 00 08 C0 02 0C 00 0D
i2c w 40 74 00 58 00 00 00 00 0D
i2c w 40 75 00 18 00 00 4C 00 0D
i2c w 40 76 15 08 00 00 34 00 0D
i2c w 40 77 14 08 50 00 0C 00 0D
i2c w 40 78 94 0A F0 00 0C 00 0D
i2c w 40 79 94 0F 00 00 54 00 0D
i2c w 40 7A 95 0E 10 00 0C 00 0D
i2c w 40 7B 01 0E D0 00 0C 00 0D
i2c w 40 7C 00 0E 00 00 AC 00 0D
i2c w 40 7D 40 2E 00 00 00 00 0D
i2c w 40 7E 40 08 70 00 0C 00 0D
i2c w 40 7F 41 08 00 00 00 00 0D
i2c w 40 80 29 48 00 00 00 00 0D
i2c w 40 81 28 08 50 00 0C 00 0D
i2c w 40 82 A8 0A F0 00 0C 00 0D
i2c w 40 83 A8 0F 00 00 54 00 0D
i2c w 40 84 A9 0E B0 06 50 00 0D
i2c w 40 85 41 08 00 00 00 00 0D
i2c w 40 86 0D 08 00 00 34 00 0D
i2c w 40 87 0C 08 50 00 0C 00 0D
i2c w 40 88 8C 0A F0 00 0C 00 0D
i2c w 40 89 8C 0F 00 00 54 00 0D
i2c w 40 8A 8D 0E 10 00 0C 00 0D
i2c w 40 8B 01 0E D0 00 0C 00 0D
i2c w 40 8C 00 0E 00 00 AC 00 0D
i2c w 40 8D 40 2E 00 00 00 00 0D
i2c w 40 8E 40 08 F0 06 94 00 0D
i2c w 40 8F 40 08 60 00 0C 00 0D
i2c w 40 90 41 08 00 00 00 00 0D
i2c w 40 91 31 48 00 00 00 00 0D
i2c w 40 92 30 08 50 00 0C 00 0D
i2c w 40 93 B0 0A F0 00 0C 00 0D
i2c w 40 94 B0 0F 00 00 54 00 0D
i2c w 40 95 B1 0E B0 06 50 00 0D
i2c w 40 96 43 08 00 00 00 00 0D
i2c w 40 97 41 08 00 00 00 00 0D
i2c w 40 98 3D 08 00 00 34 00 0D
i2c w 40 99 3C 08 50 00 0C 00 0D
i2c w 40 9A BC 0A F0 00 0C 00 0D
i2c w 40 9B BC 0F 00 00 54 00 0D
i2c w 40 9C BD 0E B0 06 50 00 0D
i2c w 47 00
i2c w 91 03
```

It is possible to read the sequencer code back from memory. This is useful to ensure that the sequencer code is correctly stored and was not accidentally changed during operation.

15.13. Pixel sequencer code read back

I2C command to imager	description / comment
`i2c w a4 00`	`#disable acquisition`
`i2c w 91 00`	`#stop sequencer`

`i2c w 40 00`
`i2c w 47 09`
`Data0 = i2c r 41`
`Data1 = i2c r 42`
`Data2 = i2c r 43`
`Data3 = i2c r 44`
`Data4 = i2c r 45`
`Data5 = i2c r 46`
	`#set dedicated sequencer RAM address (e.g. address 0x00)`
	`#enable pixel sequencer RAM access`

`i2c w 40 01`
`i2c w 47 09`
`Data0 = i2c r 41`
`Data1 = i2c r 42`
`Data2 = i2c r 43`
`Data3 = i2c r 44`
`Data4 = i2c r 45`
`Data5 = i2c r 46`
	`#set dedicated sequencer RAM address (e.g. address 0x01)`
	`#enable pixel sequencer RAM access`

...	...
`i2c w 47 00`	`#disable pixel sequencer RAM access`
`i2c w 91 03`	`#start sequencer`

Read back results (Sequencer V11)

RAM address pixel sequencer	Data0	Data1	Data2	Data3	Data4	Data5
0x00	**0x43**	**0x10**	**0x00**	**0xC0**	**0x00**	**0x00**
0x01	**0x43**	**0x10**	**0x00**	**0x00**	**0x01**	**0x00**
...	...	...	...	...	...	...

16. Addendum

16.1. Terms, definitions and abbreviations

Abbreviation	Term, Definition	Explanation
ABS	Automatic Backlight Suppression	
ADC	Analog Digital Converter	
AMR	Ambient-light to Modulated light ratio	
CGU	Clock Generation Unit	
CSP	Chip Scale Package	
DCS	Differential Correlation Sample	
DLL	Delay Locked Loop	Delay line only in the implementation of epc660
fps	Frames per second	
Half-QQVGA	1/8 of a Quarter VGA	160x60 pixel resolution
HDR	High Dynamic Range	
IC	Integrated Circuit	
LED/LD	Light Emitting Diode / Laser Diode	
LSB	Least Significant Bit	
MGA	Modulation Gate A	
MGB	Modulation Gate B	
MGX	Modulation Gate A or B	
mga	MGA control signal	
mgb	MGB control signal	
mgx	MGX control signal	
MSB	Most Significant Bit	
OSC	Oscillator	
PLL	Phase Locked Loop	
ROI	Region of Interest	
QVGA	Quarter VGA	320x240 pixel resolution
SGA	Storage Gate A	
SGB	Storage Gate B	
SGX	Storage Gate A or B	
TCMI	TOF Camera Module Interface	
TOF	Time of Flight	
VGA	Video Graphics Array	640x480 pixel resolution
XTAL	Crystal	

Table 38: Definitions and abbreviations

16.2. Related documents

- 3D-TOF, A guideline to 3D-TOF sensors that work, Beat De Coi, ISBN 978-3-033-07096-7.
- Application note AN08 Process-Rules CSP Assembly, ESPROS Photonics corp.
- Application note AN10 Calibration and compensation of Cameras using ESPROS TOF Chips, ESPROS Photonics corp.
- Application note AN11 DME 660 Photobiological Safety Analysis, ESPROS Photonics Corp.
- Application note AN12 TOF data improvement toolbox, ESPROS Photonics Corp.
- NXP I^2C-bus specification: I^2C Bus Specification and User Manual, NXP corp.

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