HELICAM C3

REVISION	DATE	DESCRIPTION OF EVOLUTION
1.15	31.01.2017	Updated chapter package contents, added sensor specs for S3.1
1.14	29.06.2016	Corrected Znew formula in chapter 5.3.3 minimize energy
1.13	8.01.2016	Added information about the minimize energy algorithm and S3.1, formating
1.12	5.11.2015	Register typos after jv review
1.11	26.10.2015	Phase correction by pi/4, typos
1.10	02.04.2015	Updated chapter 5.4 and added chapter 5.5
1.9	30.03.2015	Extended chapter 5.3.4 by deltaZ feature
1.8	24.02.2015	Added chapter 5.3.4 First surface, updated introduction
1.7	10.10.2014	Changed chapter 7 software examples
1.6	19.09.2014	Language/typos revision
1.5	05.09.2014	Added ExtTqp on IN4 for deliveries from Q1 2014. Additional smaller changes
1.4	22.07.2014	Updated different part of the document and added appendix a) + b)
1.3	24.07.2013	Added description of *Extended Simple Max Mode*
1.2	28.06.2013	Added frame rate considerations for ExtTqp mode in chapter 4.4 ExtTqp
1.1	18.06.2013	SensCaldur calculation adapted, CalDur1Cyc adapted to driver implementation, picture with open connector board removed, typos
1	11.01.2013	Creation of Version 1.0 (beta)

TABLE OF CONTENT

1. INTRODUCTION

The *heliCam C3* has been designed for real-time 3D imaging applications based on Optical Coherence Tomography (OCT). In this configuration, the sample under test is illuminated by a low-coherence light source. The light reflected from the sample is combined with a reference signal, leading to an interferometric signal that is further processed to yield depth information. Heliotis' novel approach is based on a proprietary CMOS image sensor where every pixel can acquire and process the optical signals in parallel (known as "smart pixel" technology). Each pixel of the image sensor features an electronic circuit that performs a real-time analogue preprocessing. A single sweep of the reference mirror allows a scan through the complete sample and yields a full 3D tomographic or topographic image.

Heliotis' Helicam camera also offers a number of unique characteristics that are useful for measurement applications beyond OCT. Each pixel contains a low-power signal demodulation circuit which allows simultaneous detection of the envelope and phase information of an optical interferometry signal or other amplitude modulated signals where the carrier frequency doesn't exceed 250 kHz. Also incorporated at pixel level are an automatic photocurrent offset-compensation circuit, a synchronous sampling stage and a programmable time averaging. The massive parallel detection and signal processing enables an internal frame rate of more than one million 2D pictures per second and an external frame rate of up to 3800 full frames per second. The camera features different acquisition modes for tomographic and topographic applications with flexible parameter adjustment. Depending on the scan range and camera settings more than ten processed 3D surfaces per second can be transferred to a host computer.

The heliViewer software allows the configuration of the camera. The same software also manages the data transfer as well as the data analysis functions. The software comes with a Graphical User Interface (GUI). Programming knowledge is therefore not required. This software is a compiled Labview application. Further, demo software packages in C/C++, Python and LabView for interfacing the camera are available after the installation of the driver.

This user manual contains important information to get started with the camera. The initial sections cover the hardware and software installation. The later sections describe the main camera modes. The last section includes technical data that may be useful in developing your application.

2. HARDWARE INSTALLATION

This chapter describes the delivered hardware components as well as the different triggering modes as these are strongly related to how the camera has to be connected.

2.1 PACKAGE CONTENTS

The heliCam C3 is delivered with two different sets of accessories.

2.1.1 BASIC CABLE OPTION

This package contains the following components:

1. HeliCam C3 lock-in camera
2. 2m USB 2.0 cable
3. Standard 1m connection cable (see appendix A for pinning)

2.1.2 FULL LAB CABLE KIT WITH HELIDRIVER

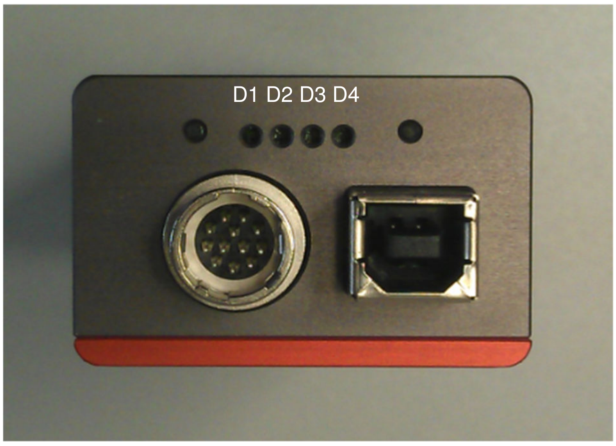
This package contains the following components:

1. HeliCam C3 lock-in camera
2. heliDriver (connection module, with integrated signal conditioning)
3. lab cable kit as following: (0.5m supply cable with banana plugs for lab supply, 1m extTqp cable, 2m trigger cable,2m camera cable, 2m USB cable)

2.2 THE HELICAM 3.0 LOCK-IN CAMERA

2.2.1 CONNECTOR SIDE

The connector side of the camera is equipped with a 12Pin Power Supply, Trigger and I/O connector and a USB Typ B receptacle. The four holes in the center allow the user to see the Status LEDs inside the camera on the connector board.

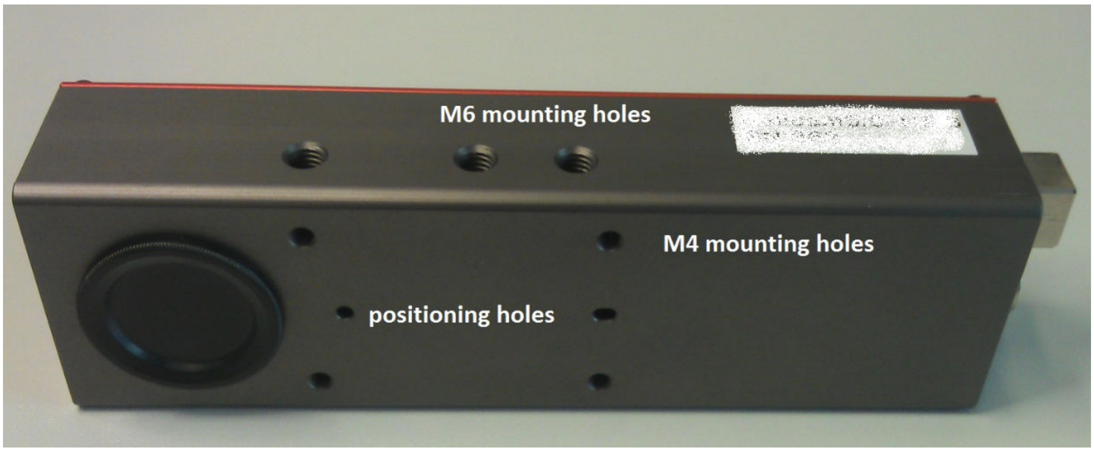


The meaning of the Status LEDs D1-D4 is described in the following table:

D1	D2	D3	D4
Volume trigger (low active)	Acquisition time out	Sensor busy signal	Ready signal

2.2.2 MOUNTING HOLES AND THERMAL REQUIRMENTS

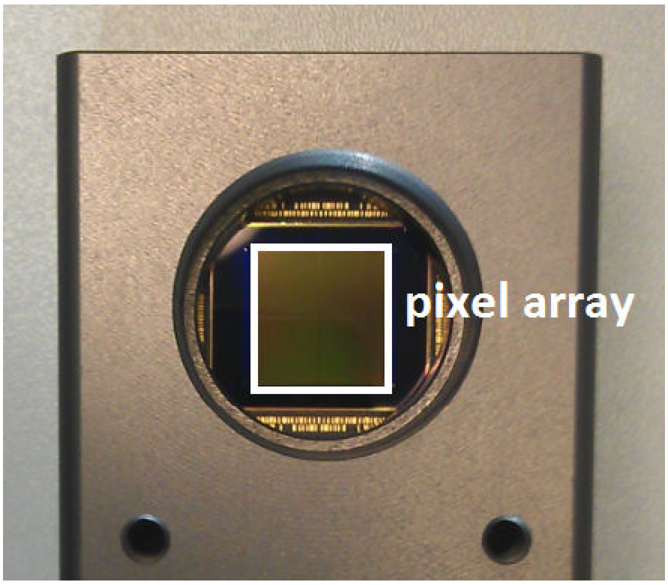
The camera can be mounted by means of 7 x M6 mounting holes, 4 x M4 mounting holes and 2x positioning holes. ***Deliveries from Q1 2014 have a slightly different housing, see appendix B for details!***



The M6 holes were originally designed for mounting the camera on an optical table. However, it is recommended to mount the camera on an additional base with good thermal conduction or to have a small fan (forced airflow) holding the temperature of the housing below 40°C. If the camera is used under controlled room temperature (20°C) and is given a good convection, additional heat sink may not be necessary.

2.2.3 LENS CAP AND SENSOR CLEANING

The camera is shipped with a lens cap. There is no additional protection (e.g. a glass) on the sensor. Therefore, take care when removing the lens cap. The optical active area of the sensor is cleaned before shipping. Yet, use a Q-tip and a 50-50 mixture of distilled water and isopropyl alcohol if the sensor has to be cleaned.

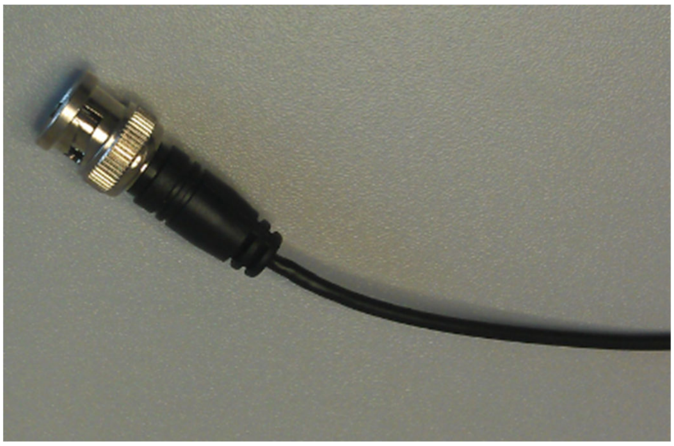


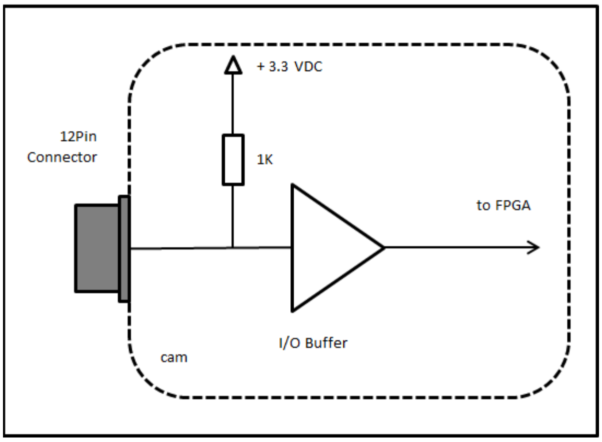
Take care not to harm the open bond wires!
To be on the safe side, clean the pixel array only.

2.3 TRIGGER CABLE

Attention: Only deliveries before Q1 2014 have a distinct trigger cable with a BNC connector. Check appendix A for the actual cable and placement of the trigger input.

The trigger cable (coax cable) is equipped with a BNC connector and is used as an input. If the correct trigger mode is configured (see chapter 4.2 External Trigger or 4.4 ExtTqp) this input *triggers* the camera to acquire a volume (a given number of frames). The following picture shows the trigger cable with the connector (left hand side) and the input circuit of the trigger signal.





The inner wire of the BNC cable is connected to Pin 9 of the camera connector and the shield is connected to GND of the camera (Pin 10). A 1KΩ pull-up resistor to 3.3V is integrated in the camera.

Ideally the external trigger signal meets the following characteristics:

- An open collector circuit shortens the input to GND. The falling edge of the trigger pulse defines the start of the measurement.
- Signal width: > 10 µs.

2.4 INTERFACE CABLE

Attention: Only deliveries before Q1 2014 have a distinct interface cable. Check appendix A for the actual cable and placement of the IOs.

The interface cable is not used in every application and only in few applications all of the signals are used. The cable therefore comes without any pre-assembled connector.

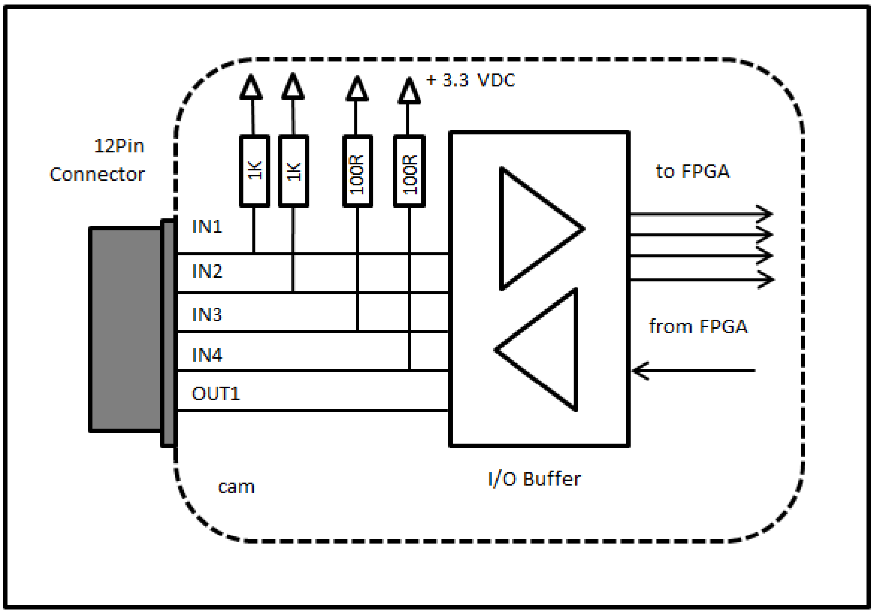
The following table describes the bare interface cable coming out of the 12Pin Hirose connector.

wire	color	direction	function	Pin # Hirose connector
w1	brown	OUT1	Synch.	6
w2	grey	IN1	*	7
w3	white	IN2	*	8
w4	green	IN3	Encoder phiA / EXTTQP Trg	11
w5	yellow	IN4	Encoder phiB	12
w6	shield	-	Connected to GND	10

* reserved

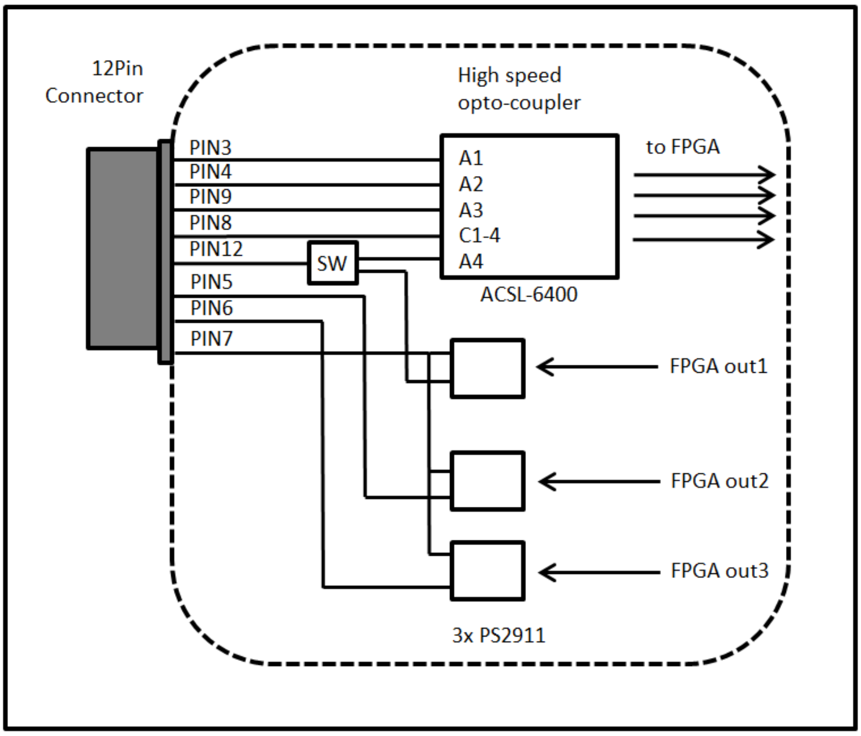
1) Pin 10 and Pin 2 of the 12Pin Hirose connector are connected to camera's GND.

The I/O circuit inside the camera looks as follows:



El. Signal specifications of OUT1**:** CMOS 3.3V, 4mA max.

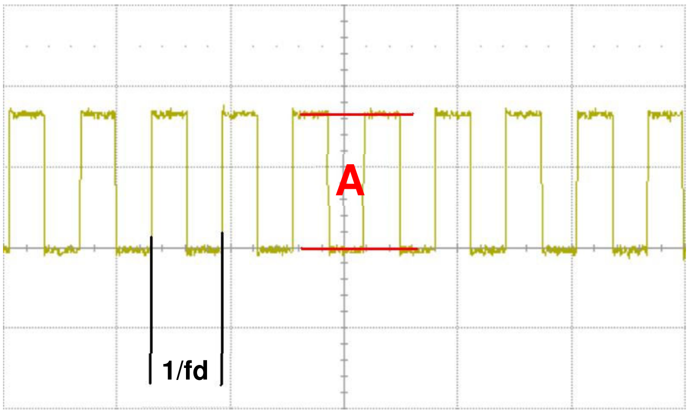
For deliveries from Q1 2014 as well as for deliveries with the heliDriver the camera IOs are opto-coupled according to the following figure:



Pin 12 can be configured as input or as output via the switch (SW). PIN 8 has to be connected to "userGND" and Pin 7 to "userVDD" if any of the camera outputs are used. The camera inputs can be used at voltages from 4.5V to 6V. The input current for the internal opto-couplers needs to be between 8mA and 15mA. The maximum input voltage on “userVDD” is 36VDC, the maximum output current is 5mA.

2.4.1 SYNCHRONIZATION SIGNAL OUT1

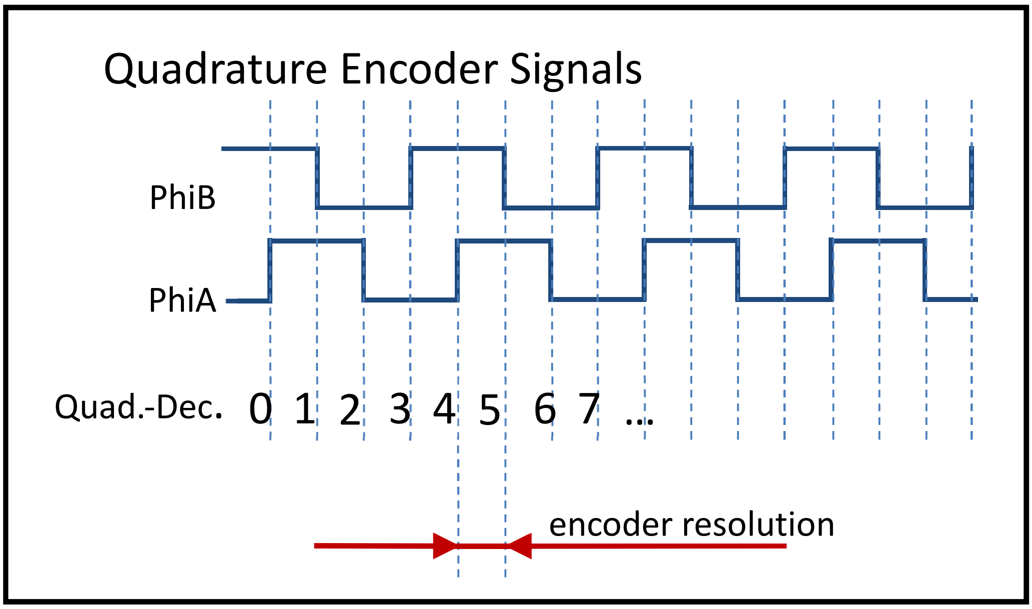
If the correct trigger mode is configured (see chapter 4.1 Internal Trigger, 4.2 External Trigger, 4.3 Trigger On Position) a synchronization signal is available on OUT1. Some applications need to be synchronized with the pixel internal lock-in frequency fd (e.g. to modulate a light source). The following rectangular signal with the above electrical specifications can be used:



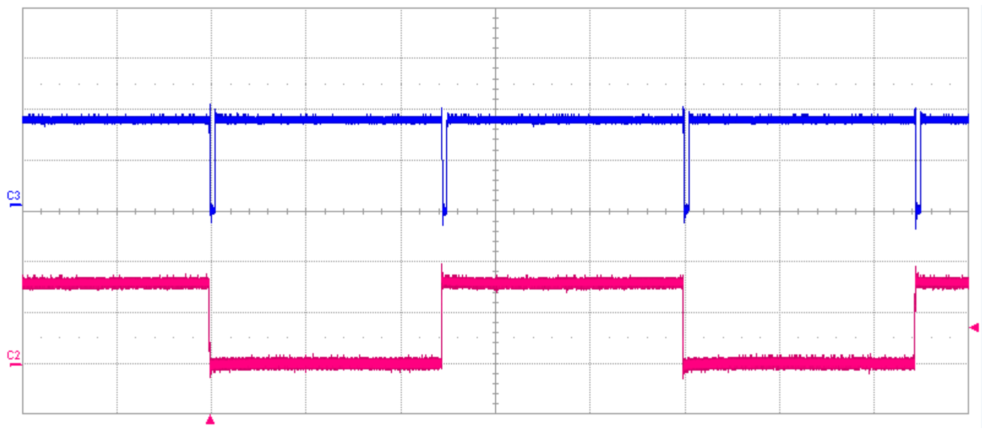
The frequency of the signal exactly corresponds to the configured lock-in frequency i.e. the demodulation frequency fd.

2.4.2 INPUTS FOR INCREMENTAL ENCODER SIGNALS IN3/IN4

IN3 and IN4 are inputs for quadrature encoder signals used e.g. to distinguish the exact position of the linear axis. The signals are processed by an internal quadrature decoder unit and a 32Bit position counter. The least significant 16Bit of the position counter are saved for every frame and returned to the header of the volume data (see *Register description* chapter *3 Header*). The following figure shows typical digital encoder signals and the corresponding result in the position counter.



If the correct trigger mode is configured (see chapter 4.4 ExtTqp Trigger) IN3 is additionally used to trigger the quarter period in-pixel integration. The goal is to synchronize the sensor's demodulation process with the movement of the stage. The following figure shows IN3/PhiA ***deliveries from Q3 2014 IN4/PhiB*** (channel 2, pink) and the resulting pulses that are generated inside the camera (channel 3, blue) for triggering the integration process:



Note that a pulse is generated on the rising and on the falling edge of IN3/PhiA. ***Deliveries from Q3 2014 IN4/PhiB!***

For deliveries from Q3 2014 pulses can be generated on both channels by setting the register "AcqCtrl.ExtTqpPuls" (Addr 0x03 bit 7) to 1. See register description file.

3. SOFTWARE INSTALLATION

Follow the information of the ReadMe.txt file supplied with the software package.

4. CAMERA TRIGGERING MODES

There are different possibilities to trigger the camera to start a measurement. Some of the triggering features may exclude some modes or may have other implications. This chapter describes all the triggering modes and exact register settings of the camera.

The following table gives an overview of the trigger modes and register settings:

× : don't care

✓ : fully usable and has to be set by the user's application (see detailed description of the mode)

	Camera Registers							**BNC Trigger input**	**Interface cable**	**Intensity Mode**
	TrigFreeExtN	ExtTqp	EnTrigOnPos	ClrPosCnt	TrgDown	MskTrgOnPos	TrigOnPos			
1) **Internal Trigger**	= 1	×	×	×	×	×	×	not used	not used	available
2) **External Trigger**	= 0	= 0	= 0	×	×	×	×	used	not used	available
3) **Trigger On Position**	= 0	= 0	= 1	✓	✓	✓	✓	optional	used	available
4) **ExtTQP Trigger**	= 0	= 1	= 0	×	×	×	×	used	used	not available
5) **Trigger On Position + ExtTqp Trigger**	= 0	= 1	= 1	✓	✓	✓	✓	optional	used	not available

4.1 INTERNAL TRIGGER

Must have Register setting:

- *TrigFreeExtN = 1*

Optional registers:

- *EnSynFOut: [0 or 1], Synchronization signal on OUT1*

Most applications don't use the internal trigger mode in their final configuration. However, it is recommended to use this mode to get started with the HeliCam and to align the optical setup.

In this mode the camera starts capturing frames automatically and saves them in its RAM. The user's program, the HeliCam Viewer or one of the sample programs installed with the driver can always acquire data.

4.2 EXTERNAL TRIGGER

Must have Register setting:

- *TrigFreeExtN = 0*
- *ExtTqp = 0*
- *EnTrigOnPos = 0*

Optional registers:

- *EnSynFOut: [0 or 1], Synchronization signal on OUT1*

Must have connections:

- *Trigger cable*

Most applications use this setting. The camera starts capturing frames on a pulse of the external trigger input (see chapter 2.3 Trigger cable for the electrical specifications).

4.3 TRIGGER ON POSITION

Must have Register setting:

- *TrigFreeExtN = 0*
- *ExtTqp = 0*
- *EnTrigOnPos = 1*
- *TrigOnPos: [0 to 2^{32}-1], desired value for the trigger position from*
- *TrgDown: [0 or 1]*

Optional registers:

- *ClrPosCnt: [0 or 1], clears the position counter if set to 1*
- *MskTrgOnPos: [0 or 1], masks the clear by external trigger feature*
- *EnSynFOut: [0 or 1], Synchronization signal on OUT1*

Must have connections:

- *The encoder inputs of the interface cable (IN3/IN4) have to be connected to a digital incremental encoder stage (see chapter 2.4.2).*

In this mode the value of the in camera position counter is compared with the 32Bit register value **TrigOnPos** which is set by the user. With **TrgDown=0** the trigger is generated when passing TrigOnPos from smaller to bigger values. Vice versa with **TrgDown=1** the trigger is generated when passing TrigOnPos from bigger to smaller values.

The position counter can be set to zero by setting the register **ClrPosCnt=1** and **ClrPosCnt=0** (ClrPosCnt=1 will hold the position counter on value 0). On the other hand the counter is cleared when a trigger signal is generated on the trigger input (see chapter 2.3). This feature can be disabled by setting the **MskTrgOnPos=1**. For example the trigger input could be connected to the reference index of a linear scale. To set MskTrgOnPos=1 after the clearing of the counter prevents an unwanted resetting of the counter.

Further, the least significant 16Bit of the position counter are saved for every captured frame and returned to the header of the volume data (see *Register Description* document chapter *3 Header*).

4.4 EXTTQP TRIGGER

Must have Register setting:

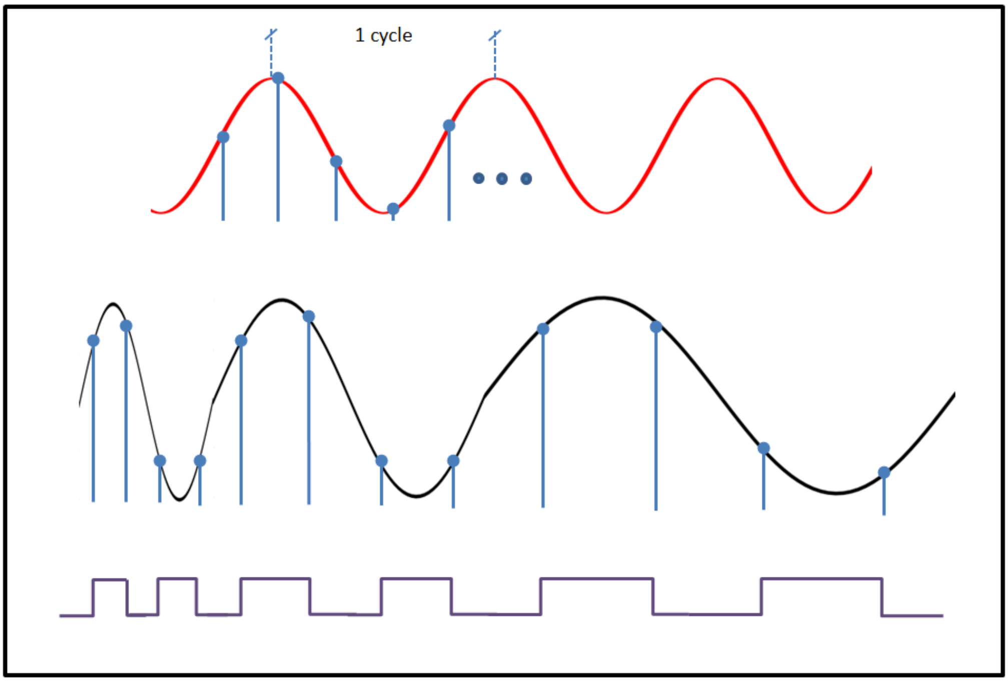
- *TrigFreeExtN = 0*
- *ExtTqp = 1*
- *EnTrigOnPos = 0*

Must have connections:

- *At least PhiA (IN3)* ***deliveries from Q3 2014 IN4/PhiB*** *from the encoder inputs has to be connected. The electrical specifications are described in chapter 2.4.2.*
- *Trigger cable*

Some applications may rather synchronize the in-pixel demodulation process to the modulation of the light (that may e.g. be given by the scanner passing the coherence plane in an interferometer setup) than the other way round. In the *ExtTqp* triggering mode, IN3 ***deliveries from Q3 2014 IN4*** defines the start of an integration process of the sensor. The start of the measurement is given by a pulse on the trigger input (see chapter 4.2). The pulses that are generated by toggling IN3 (see chapter 2.4.2.) ***deliveries from Q3 2014 IN4/PhiB*** start the integration of quarter periods (TQP = **t**ime **q**uarter **p**eriod) on the sensor. Consequently, for every cycle four samples are taken to run the in-pixel demodulation process properly.

The following figure shows this fact:



The first sampled sine wave (red) shows the “normal” mode without having the demodulation process triggered by the user. The samples are taken in equidistant time intervals. The time interval is defined by the register **SensTqp**. The exact formula is as follows:

$\Delta T = 2 * (SensTqp + 30) / fs$ with: sensor frequency fs = 70MHz

The lock-in demodulation frequency fd is therefore given by:

$fd = 1/(4\ \Delta T)$

Let’s take a linear axis with a non-constant velocity passing the interference plane. The resulting sine wave could be something similar to the frequency modulated sine wave (black) shown in the figure above. Of course, an equidistant sampling of the signal would result in corrupt measurements. In such a case, the user can fully control the sampling time with a rectangular signal on input **IN3** ***deliveries from Q3 2014 IN4***. Samples are generated on the rising and falling edges (see chapter 2.4.2).

Further, the SensTqp Register defines the integration duration of one sample. In such a setup, care must be taken when choosing the value for SensTqp. The following criteria have to be fulfilled:

$(SensTqp + 11) * 1/35Mhz < T_{pulsewidth}$

with $T_{pulsewidth}$: pulsewidth of the rectangular signal on IN3

Theoretical maximum for SensTqp:

If encoder signals are used (as described in chapter 2.4.2) the limit for the SensTqp parameter is given by the following formula:

$(SensTqp + 11) * 1/35Mhz < 2 * EncRes/v_{max}$

with EncRes: resolution of the encoder [mm] (see definition in chapter 2.4.2)

v_{max}: maximum velocity of the scanner during measurement [mm/s]

Considering the maximum framerate of the camera:

If encoder signals are used (as described in chapter 2.4.2) the frame rate of the camera is given by the value of SensNavM2, the average speed of the scale v_{avg} during a frame and the encoder resolution EncRes (as described in chapter 2.4.2).

The system setup has to meet the following inequation:

$MaxFramerate > v_{avg} / (8 * EncRes * (2*SensNavM2 + 3))$, with BSEnable=1 and CalDur1Cyc=1

$MaxFramerate > v_{avg} / (16 * EncRes * (SensNavM2 + 1))$, with BSEnable=0

The maximum frame rate of the camera MaxFramerate is: 3800 fr/s (see chapter 8)

4.5 COMBINED TRIGGER ON POSITION AND EXTTQP TRIGGER

Must have Register setting:

- *TrigFreeExtN = 0*
- *ExtTqp = 1*
- *EnTrigOnPos = 1*
- *TrigOnPos: [0 to 2^{32}-1], desired value for the trigger position*
- *TrgDown: [0 or 1]*

Optional registers:

- *ClrPosCnt: [0 or 1], clears the position counter if set to 1*
- *MskTrgOnPos: [0 or 1], masks the clear by external trigger feature*

Must have connections:

- *At least PhiA (IN3)* ***deliveries from Q3 2014 IN4/PhiB*** *from the encoder inputs has to be connected with the electrical specifications described in chapter 2.4.2.*
- *Trigger cable*

The two modes described in 4.3 and 4.4 can be combined.

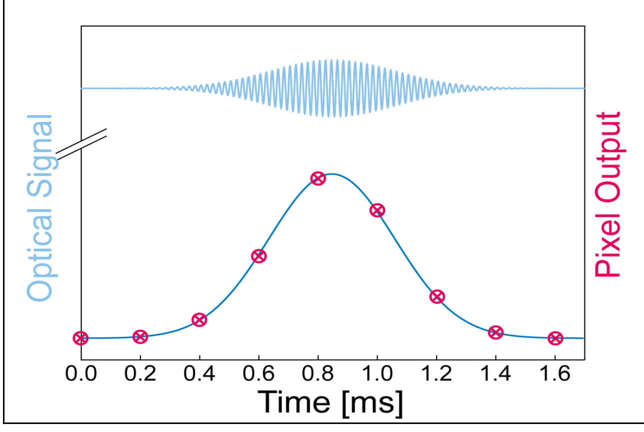
5. CAMERA ACQUISITION MODES

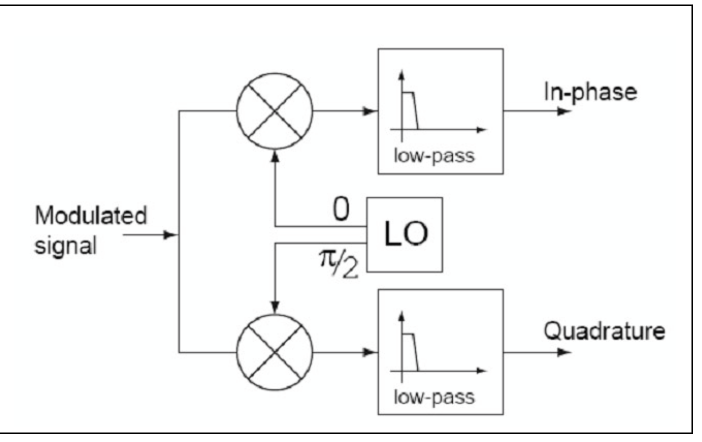
5.1 MEASURE RAW IQ

Must have Register setting:

- *CamMode = 0*

The camera is designed to detect the modulated part of the light in every pixel. The demodulation process at pixel level can be described as follows: The incoming modulated light signal is multiplied by a sine and a cosine coming from a fixed frequency local oscillator (LO) at demodulation frequency fd. These two signals are integrated over N_c cycles (Low-pass over a given number of cycles). The results are the two In-phase (I) and Quadrature (Q) values that are returned by the sensor. This measurement is repeated N_{fr} times (with N_{fr}: Number of frames).





Raw IQ:

In the **Raw IQ** mode *raw_I* and *raw_Q* values are returned.They range from 0 to 1023 (10 bit) and are therefore returned in an unsigned u10.0 format. The value of *raw_I* and *raw_Q* corresponding to a non modulated signal is not 0 but around 512. First these *offset_I* and *offset_Q* values should be measured for every pixel and then subtracted from *raw_I* and *raw_Q* to get the actual I and Q values (can be positive or negative).

I = raw_I-offset_I and Q = raw_Q-offset_Q

Once I and Q are calculated, the amplitude and phase of the modulated signal can be obtained by the formula:

Amplitude=sqrt(I^2+Q^2) and Phase=atan2(I,Q) - π/4

There are several strategies to get the offset_I and offset_Q values:

- *One way to calculate the offset is to find a few frames where the signal surely isn't modulated. Taking the average of these frames will give you the offset. This is one method implemented in the camera (*Register *OffsetMethod=1).*

- *A slightly different frequency can be chosen for the modulation of the light and the Lock-In camera. As a consequence, I and Q will oscillate progressively between their min and max values from frame to frame, doing a sine and a cosine. Dividing the peak-peak values of these sine and cosine by 2 will give the offset_I and offset_Q.*

- *When most of the time no modulated signal is present, one can take the most frequent value from a histogram for every pixel. This is the other method employed in the amplitude mode integrated into the camera (*Register *OffsetMethod=0).*

5.2 MEASURE AMPLITUDE

5.2.1 AMPLITUDE

Must have Register setting:

- *CamMode = 1*

Optional registers:

- OffsetMethod = [0 v 1], default '0'

In the "Amplitude" mode the previous calculation is done directly in the camera. The algorithm used to measure the *offset_I* and *offset_Q* can be chosen by the user by the register *OffsetMethod* in the camera (a histogram and an average based method can be chosen, see register description document). The returned 16Bit value is the amplitude interpreted as a u12.4 format (unsigned fixpoint value with 12Bit> 1 and 4 Bit < 1).The phase information is not transferred.

5.2.2 SMOOTHED AMPLITUDE

Must have Register setting:

- *CamMode = 2*

Optional registers:

- FWHMnFrame

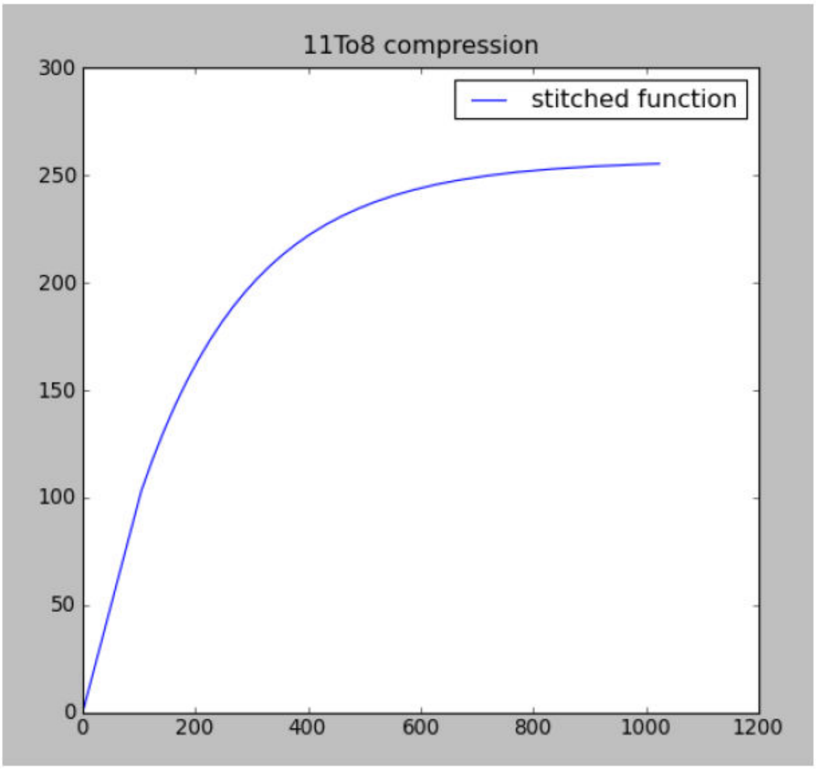
There is the possibility to have a filtered signal in the amplitude mode, i.e. the smoothed Amplitude mode. The length of the filter can be set by the user by the register *FWHMnFrame*. Thus, the user may configure a "mathed-filter" where the form of the signal i.e. of the signal-envelope corresponds to the impulse response h(t) of the filter. Maximizing the SNR is the goal of this feature. The format of the returned amplitude is also u12.4.

5.2.3 COMPRESSED AMPLITUDE

Must have Register setting:

- *CamMode = [1 v 2]*
- Comp11to8=1

In both modes *Amplitude* and *Smoothed Amplitude* the values can be compressed to 8Bit to reduce the amount of data and transfer time to the host computer. Set the register **Comp11to8=1** to get compressed amplitude data. The data format of the returned amplitude is then u8.0. The following function is used for compression:



The function is a combination of two parts:

$$f(x) = x \; for \; x = \{0..100\}, 156 \times \left(1 - e^{(0.5 - 0.005x)}\right) + 100 \; for \; x = \{101..1023\}$$

5.3 MEASURE SURFACE

As the amount of data in *rawIQ* and amplitude modes is quite huge, the interface to the host computer is a limiting factor. The camera provides the possibility to calculate and transmit a surface extracted from the volume. Originally, the algorithm was developed for OCT topology measurements i.e. for opaque surfaces returning only one interference-fringe per A-scan in a white light interferometer setup. This means that the algorithm works well for volumes/signals with only one envelope. If the signal has multiple envelopes the algorithm snaps to the one with the strongest amplitude (which might not always be the correct one).

5.3.1 SIMPLE MAX

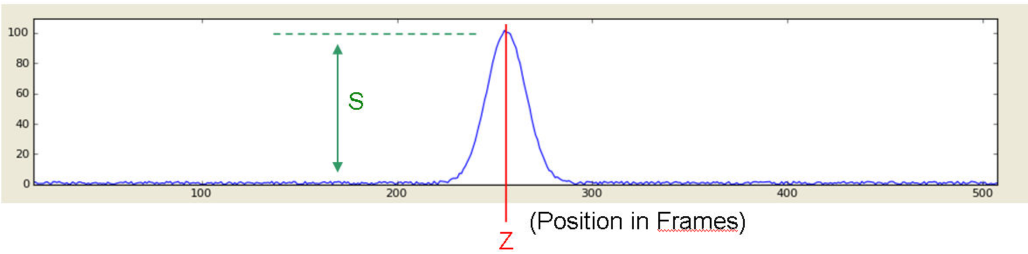
Must have Register setting:

- *CamMode = 4*

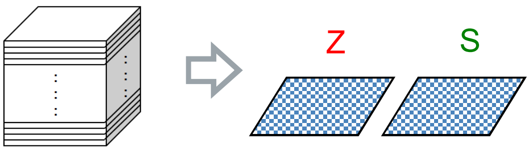
Optional registers:

- FWHMnFrame

In this mode the maximum signal strength S and the corresponding Z values are saved for every pixel. The Z value defines the position (on which frame the maximum was found) in the volume. For the following example a maximum signal strength S of 100 has been found on frame number 250. Therefore Z=250 and S=100.



In the surface modes *SimpleMax* and *MinEnergy*, only the S and the Z values for every pixel are transferred to the host computer. The S value is stored in an u12.4 (16Bit) and the Z value in an u11.5 (16Bit) format. Thus only 32Bit per pixel are transferred. The compression factor scales with the number of frames taken for a volume. For example in the *rawIQ* mode with 400 frames the compression factor is 250. The following figure shows a volume from where the height in Z and the signal strength in S are extracted:



Furthermore, with the Number of frames N_{fr} (Register SensNFrames) set to 100 around 20 3D-images per second can be acquired.

5.3.2 EXTENDED SIMPLE MAX

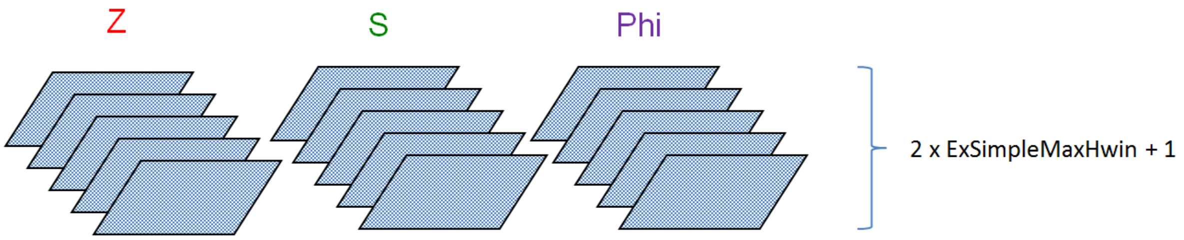
Must have Register setting:

- *CamMode = 5*
- *ExSimpMaxHwin*

Optional registers:

- FWHMnFrame
- SigTsh (values bellow are considered as noise)

In this mode the camera not only transmits for every pixel the data from the simple max (see 5.3.1), which is *16Bit Amplitude **Smax** and 16Bit FrameNumber **Zmax***, but also a given number of additional Amplitude A - and Phase φ values around the maximum. The number of the additional values around the maximum (half window size) is defined by the user by setting the register *ExSimpMaxHwin*. Legal values are 1..10. This results in a minimum of 9 (3x3) and a maximum of 63 values (3x21) per pixel.



The data format of the values is as follows:

Surface Z	Unsigned (11.5)
Amplitude S	Unsigned (12.4)
Phase Phi	Unsigned (3.13)

With this additional information given in this mode the user has

a) A fast acquisition mode

b) Still enough data to implement own fitting algorithms (e.g. with the use of the additional Amplitude S values and/or the phase values) to find the true maxima of the envelope.

5.3.3 MINIMIZE ENERGY

Must have Register setting:

- *CamMode = 7*

Optional registers:

- FWHMnFrame
- IterCtrl
- IterMaxInt
- IterMaxFrac
- MinEnergWin
- UnderRelParam

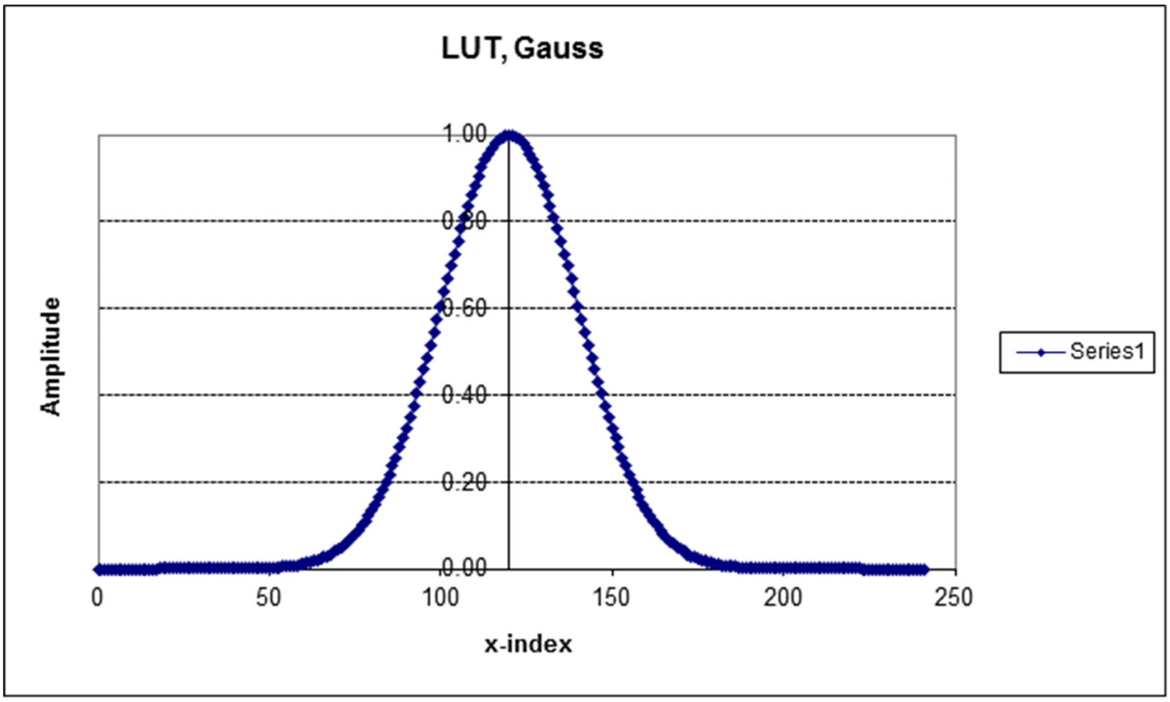
Using this mode two options are available: The normal *IntegerMode* (IterCtrl=1) and a *FractionalMode* (IterCtrl=2). The *FractionalMode* gives sub-frame resolution by fitting a parabola through the three points around the maximum in Z. This takes place after the minimize energy which makes the *FractionalMode* mode slightly slower than *IntegerMode*.

The *Minimize Energy* is based on *Simple Max* which means that for every pixel the corresponding S and Z values are calculated first. The general intension of the algorithm is to find a Z value that fits best to the neighbouring Z values (where the energy is minimized). Therefore, the ΔZ from the pixel to be calculated (for example 'a' in the figure bellow) and the weighted average of the neighbouring Z_{nb} (defined by pixels 1,2,3,4) are placed into a quality function taking these two parameters and giving back the best Z.

The quality function returns the maximum value inside the minimize Energy window 2* *MinEnergWin* (Register 0x4e) centered around Z_{nb}. Mathematically the function can be expressed like this:

$$Zbest = \max(Ascan[n] \times e^{-\frac{1}{2}\left(\frac{Z[n]-Znb}{\sigma}\right)^2}, n\ in \pm MinEnergWin)$$

It can be seen that the quality function picks out the maximum value described by a limited Gaussian bell curve with the weighted average Z_{nb} as the expectation value. For the implementation in the FPGA the function is pre-calculated with a standard deviation of *σ=20.* The following figure shows the values of the look up table LUT in the FPGA.



The LUT consist of 241 values including the maximum value at position x=120.

Under Relaxation parameter *UndRelParam*:

After finding the best Z value (Zbest) with the aid of the quality function the distance between the best Z and the Z from the last iteration (Zlast) is weighted with the UndRelParam value.

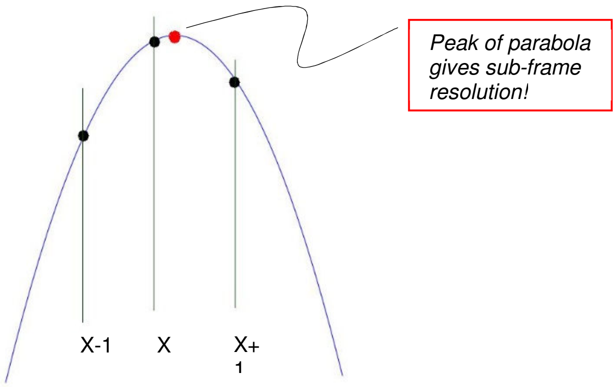
$$Znew = Zlast + (Zbest - Zlast) \times UndRelParam$$

UndRelParam is an U0.8 register with default value of 0.75 (see register description file for details).

Sub-frame resolution by parabola fit:

When pixel "a" is updated, it might change the average value of the neighbouring Z_{nb} significantly when calculating pixel "3" for example. Therefore, it might be necessary to update the pixels several times until they converge to a value. Obviously it is an iterative procedure. The maximum number of iterations can be defined in the registers *IterMaxInt* and *IterMaxFrac*.

The following figure illustrates how the sub-frame resolution is achieved. X is the frame with maximum signal strength (or amplitude) S. The maximum of the envelope, or in this case of the fitted parabola, is between frame X and frame X+1.



Based on the fact that the 16Bit Z-values are interpreted as a U11.5 a sub-frame resolution of 2^{-5} is achieved.

5.3.4 FIRST SURFACE

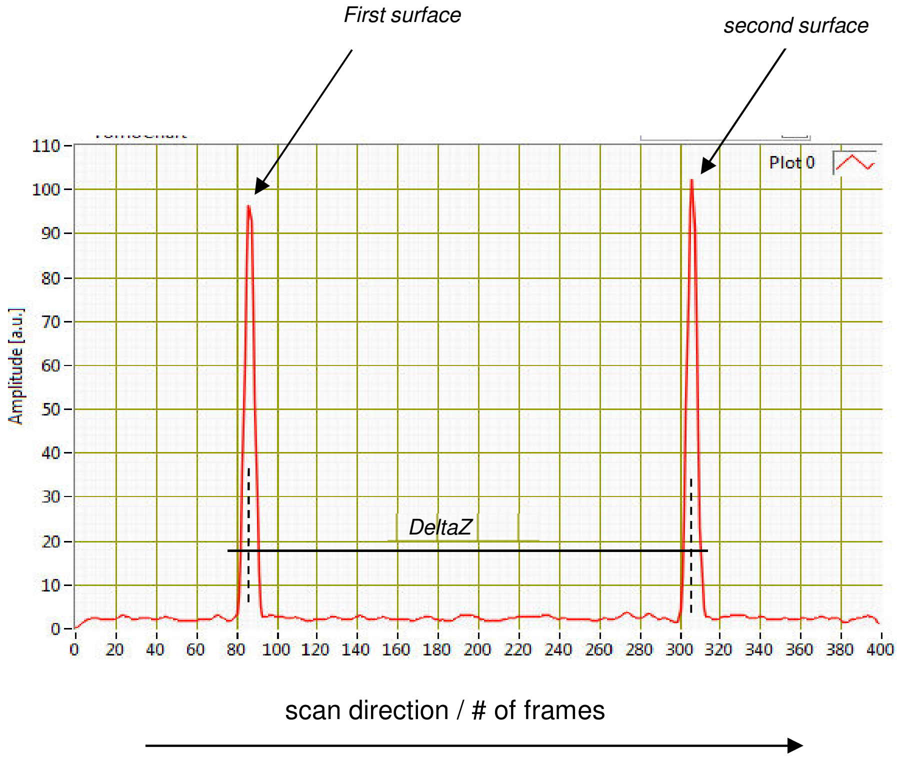
Must have Register setting:

- *CamMode = 4 or CamMode = 7*
- *EnFirstSurf=1*
- *FirstSurfAtsh*

Optional registers:

- *EnMaxUnderTsh*
- *EnDiffuseSurf*
- *EnLastSurf*
- *EnDeltaZ*
- *… all registers used when using commode 4/7*

Some transparent and semitransparent samples often do return more than one surface i.e. for one volume the interferometer returns multiple fringe pattern and therefore returning a true tomographic signal. The result of a pixel plotted in the z-direction from such a sample may return the following signal:



If the “First Surface” is not enabled *EnFirstSurf=0* the surface algorithms (commode 4 and 7) will find or snap to the “second surface” (Z=308 and A=102). By setting *EnFirstSurf=1* and choosing an appropriate value for *FirstSurfAtsh* the algorithms will snap to the “First surface” with the values Z=86 and A=96.

The threshold value *FirstSurfAtsh* has to be set in an **unsigned 10.4** format. For the above example a threshold value of 10 would work well. This means the value for *FirstSurfAtsh* has to be set to:

FirstSurfAtsh = 10x16 = 160

Enable maximum search under threshold *EnMaxUnderTsh:*

Setting this register to 1 enables the maximum peak search also for pixels where the signal is below the threshold value in *FirstSurfAtsh.* Otherwise when *EnMaxUnderTsh=0* the values A and Z for these pixels will be set to zero (A=0. Z=0).

Enable diffuse surface *EnDiffuseSurf:*

Some semi-transparent surfaces may return signal over a wide range i.e. over many frames so that a peak search cannot take place. Here setting the register *EnDiffuseSurf=1* can help as the result for A and Z will be saved as soon as the signal crosses the threshold value defined in *FirstSurfAtsh. EnDiffuseSurf=0* will disable this feature.

Enable next surface *EnLastSurf:*

Setting the register *EnLastSurf=1* will start a new maximum search after every crossing from below to over threshold of the amplitude value (a transition is necessary). In the example above the “second surface” would have been found. In a multi-surface sample measurement the last surface in the volume will be picked. This feature can also be used if the scan direction is inverted and the user is still interested in the “first surface”. *EnLastSurf=0* will disable this feature.

Enable returning the difference in Z of two surfaces, *EnDeltaZ*:

Setting this register *EnDeltaZ=1* allows the user to get the height difference in Z (in number of frames) of two signals as shown in the picture above. The returned Z (DeltaZ) value of each pixel is: $\mathbf{Z_{xy} = Z2 - Z1}$.

The signal S of the returned data corresponds to the surface with the lower signal i.e. with the smaller amplitude: $\mathbf{S_{xy} = min (S1,S2)}$.

The detection of surfaces is defined by the register *FirstSurfAtsh.*

5.4 INTENSITY MODE

Must have Register setting:

- *CamMode = 3*
- *SensNFrames*
- *SensExpTime*
- *BSEnable = 0*

Optional registers:

- *SensNDarkFrames*
- *SensExpTimeMult*
- *SensExpRatio*
- *TrigFreeExtN*

In the intensity mode the HeliCam works like a standard 2D camera. The intensity mode might be useful for aligning a light beam or imaging an object similar to a consumer camera. In this mode the control electronics of the sensor is modified in such a way that not demodulated signals i.e. usual integrated signals are generated on the two channels I and Q. The sensor returns two images with different exposure times. With the camera register *SensExpTime* and *SensExpTimeMult* the exposure time from the short exposed image can be set. The exposure time is calculated by:

SensExpTime ***** (*SensExpTimeMult* + 1) (in micro seconds [µs])

The ration between short and long exposure time can be defined with the register *SensExpRatio*. This is a two bit register and the ration match to the value in the following table:

SensExpRatio (value)	*Ratio* (between short and long exposure)
0	1 : 2
1	1 : 4
2	1 : 8
3	1 : 16

The offset compensation is done by the SDK. For this, the sensor can return a defined value of “dark” images which represents an unexposed image. The SDK subtract the offset automatically from the exposed images. The number of dark frames must be *SensNDarkFrames* **≥ 7**. The user may increase this number to improve the offset calculation on the host.

With the *SensNFrames* register, the total number of measured images is defined. The SDK returns the following number of HDR (high dynamic range) images:

SensNFrames – *SensNDarkFrames* – 3

This means that the following condition must be met: *SensNDarkFrames* ≤ *SensNFrames* – 4

For the first image, the SDK returns additionally the short and long exposure image. For more information, please follow the link to your preferred programming language (listed in chapter 7).

5.5 SEGMENTED ACQUISITION FEATURE

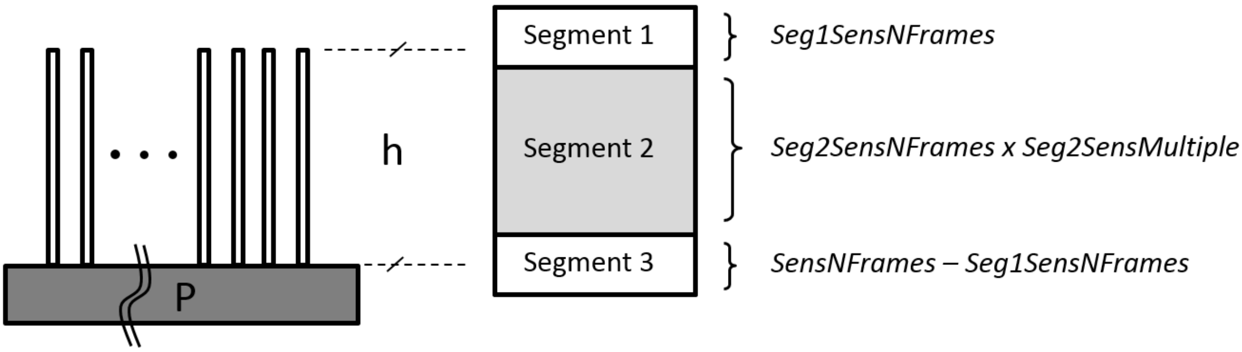
Must have Register setting:

- *SegVolume = 1*
- *Seg1SensNFrames*
- *Seg2SensNFrames*

Optional registers:

- *Seg2SensMultiple*

Some applications do need larger scan ranges where some area between the interesting segments isn’t relevant. The following figure shows such an application example where the length of the pins *h* is of interest. The region between the top of the pins and the surface of the package *P* does not hold any information for this measuring problem.



The user can configure the camera in a way that it will deliver data in *Segment 1* and in *Segment 3*. *Segment 2* will not contain data. Like this, the user has to handle less data while having the full z-resolution in Segment 1 and in *Segment 3*.

The feature is available in all camera modes by setting the register *SegVolume*=1 (0x02, Bit 2). The total number of active frames is still given by the register *SensNFrames*. The number of frames in *Segment 1* is defined by the register *Seg1SensNFrames* has to be to be smaller than the *SensNFrames* as the number of frames in *Segment 3* is given by: *SensNFrames* **-** *Seg1SensNFrames***.**

The number of frames in *Segment 2* is defined by the multiplication of two registers:

Seg2SensNFrames x *Seg2SensMultiple*

Both registers are 12Bit wide. Like this the complete scan range can be extended to a maximum of:

$$\boxed{2^{12} \times 2^{12} = 2^{24} \longrightarrow \approx 16 \text{ Million frames}}$$

6. UNDERSTANDING THE MOST SIGNIFICANT REGISTERS

The purpose of this chapter is to get an overview of the most significant sensor registers. Registers regarding a concrete acquisition / triggering mode are described in the chapters above.

- *SensNFrames*: number of frames, N_{fr} (300x300 pixel images) to be acquired. The maximum number of frames is 512.
- *SensTqp*: Determines the reference frequency of the Lock-IN camera. For a demodulation frequency fd, *SensTqp* is calculated as follows: *SensTqp*=70MHz/(8* fd)-30. E.g. if fd=10KHz, *SensTqp*=845.
- *CalDur1Cyc***:** If 1, the time T_{offset} of the offset compensation is exactly 1 cycle. If 0, you have to define a value for the register *SensCaldur* (between 1 and 4096) and the time for the offset compensation is defined by T_{offset} = (*SensCaldur* + 58)/35MHz.
- *SensNavM2***:** Number of averaging/demodulating cycles per frame N_c = *SensNavM2x2*+2. Note that in addition to N_c, if *BSEnable* is on (value 1), sometime T_{offset} is used to set the offset compensation of the pixel (to compensate DC light) before taking a frame. If *CalDur1Cyc* is set to 1, T_{offset} equals the time of one cycle.The time between 2 successive frames is given by: $T_{fr} = (N_c/ f_d)+T_{offset}$. So for example for f_d=9KHz and SensNavM2=3 the time between two frames equals 1ms (with *BSEnable*=1 and *CalDur1Cyc*=1), corresponding to a frame rate of 1000 frames/s. Take care not to exceed 3800 frames/s.
- *DdsGain*: Defines the analogue signal gain in the sensor. Measurements have shown that the best SNR is achived with DdsGain=2. The following table shows how the effective gain is coded in the *DdsGain* register:

DdsGain	Effective gain
0	3
1	1.5
2	**1**
3	0.75

- *BSEnable*: The in-pixel background suppression is on, if *BSEnable*=1. This allows to compensate the in-pixel DC part of light.

7. SOFTWARE EXAMPLES

After installing the full SDK, example programs can be found written in C/C++, LabView and Python. For a detailed description of the examples please have a look into the following documentation folders.

For C/C++: *C:\Program Files\Heliotis\heliCam\Cpp\documents*
For LabView: *C:\Program Files\Heliotis\heliCam\LabView\documents*
For Python: *C:\Program Files\Heliotis\heliCam\Python\documents*

8. SENSOR SPECIFICATION

The heliCam C3 and other heliotis products like H6, H4 and P4 are delivered

8.1 HELISENS S3.0

Parameter	**Value**
Die Size	19.71 mm x 16.89 mm
Number of Columns	300 (centre 280 usable, 2x10 columns are test columns)
Number of Rows	300 (centre 292 usable, 2x4 rows are test rows)
Total number of pixels	90'000
Column Pitch ΔX_{pixel}	39.6 µm
Row Pitch ΔY_{pixel}	39.6 µm
Photodiode dim. X $\Delta X_{photodiode}$	22.2 µm
Photodiode dim. Y $\Delta Y_{photodiode}$	12.7 µm
Photodiode area	282 µm^2
Optical fill factor	18.0 % (without micro-lenses)
Pixel Field Width	11.9 mm
Pixel Field Height	11.9 mm
Max. External Frame Rate (for current firmware)	3800 fps
Max. Demodulation Frequency	250 kHz (Equals an internal rate of 1M frames per second)
Min. Demodulation Frequency	2137Hz
Output Resolution	10 bit

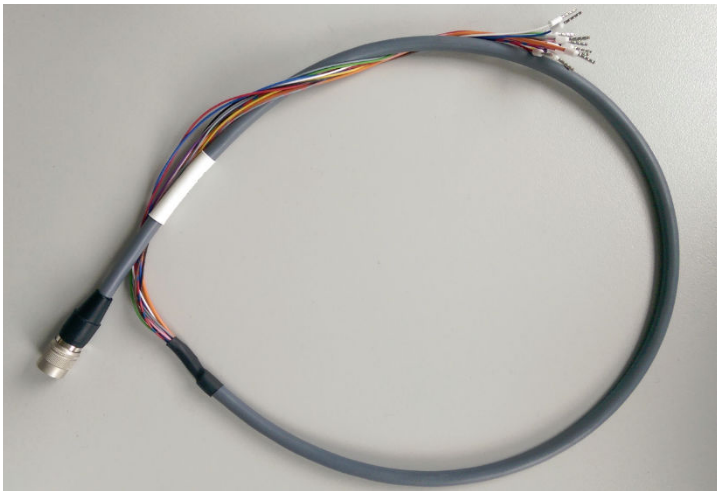
8.2 HELISENS S3.1

Parameter	Value
Die Size	19.71 mm x 16.89 mm
Number of Columns	300 (centre 280 usable, 2x10 columns are test columns)
Number of Rows	300 (centre 292 usable, 2x4 rows are test rows)
Total number of pixels	90’000
Column Pitch ΔX_{pixel}	39.6 µm
Row Pitch ΔY_{pixel}	39.6 µm
Photodiode dim. X $\Delta X_{photodiode}$	11.2 µm
Photodiode dim. Y $\Delta Y_{photodiode}$	11.2 µm
Photodiode area	125.4 µm^2
Optical fill factor	8 % (without micro-lenses)
Pixel Field Width	11.9 mm
Pixel Field Height	11.9 mm
Max. External Frame Rate (for current firmware)	3800 fps
Max. Demodulation Frequency	250 kHz (Equals an internal rate of 1M frames per second)
Min. Demodulation Frequency	2137Hz (with internal demodulation)
Output Resolution	10 bit
Responsivity (@ gain=1.5)	0.92 DU/µJ/m^2 (green) 0.1 DU/µJ/m^2 (red)
Responsivity to DC in demodulation mode (@ gain=1.5)	0.16 DU/mJ/m^2
Quantum efficiency	20-90% (@350-450nm) >90% (@450-750nm) 90-20% (@750-950nm)

9. APPENDIX

9.1 A)

Deliveries from Q1 2014 include a standard 12Pin 1m connection:



Pin #	Wire colour	description
1	Red	VDD
2	Blue	GND
3	Pink	A
4	Grey	B
5	Yellow	OutEnDrv
6	Green	OutFSync
7	Brown	UserVDD
8	White	UserGnd
9	Black	Trigger
10	Red/Blue	Driver current I_plus
11	Pink/Grey	Driver current I_minus
12	Violet	IOA
	Orange	Shield

9.2 B)

Deliveries from Q1 2014 do have a different housing with the following mounting holes: