General description

The TOFcam-635-S is a miniaturized and cost-optimized 3D TOF camera. It is based on the ESPROS proprietary time-of-flight (TOF) technology using the epc635 chip. The camera controls the illumination and the imager chip to obtain distance and grayscale images. The cameras are calibrated to provide accurate 3D depth information. The depth images are compensated against DRNU errors, modulation errors, temperature, ambient-light and reflectivity of the scene. Its extremely wide field of view of 120° allows a variety of new applications e.g. for mobile robotics or entrance controls.

This document allows a TOFcam-635-S user easily to get the camera connected and started using a computer. It contains a description of all features, commands, protocols and interfaces of the device. This allows to connect the module to integrated systems. The optional software development kit (SDK) contains the camera operating system (TOFCOS) with all C++ source codes. Together with the ESPROS epc635 evaluation kit this is the perfect environment to develop embedded software or even an application specific camera.

Figure 1: TOFcam-635-S

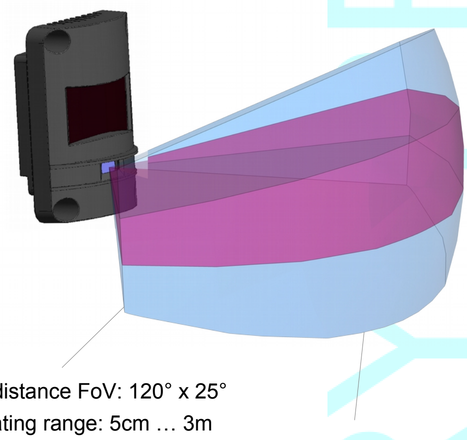


Figure 2: TOF and gray scale field definition

Features

- ■ 160 x 60 pixels resolution
- ■ Field of view of 120° x 25° for TOF images
  Field of view of 120° x 45° for gray scale images
- ■ Distance measurement ranges on white target: 5cm … 3m
- ■ Measurement rate up to 20 TOF measurements per second
- ■ Fully calibrated and compensated
- ■ USB interface
- ■ High speed serial interface UART 10 Mbit/s
- ■ Two I/O versions available
- ■ Low power consumption
- ■ Various user interfaces: GUI, ROS, Python
  - □ Evaluation of TOFcam-635-S features
  - □ Programming of I/O properties
  - □ Store and recall camera configurations
  - □ Many explanations about “time of flight done right”

Typical applications

- ■ Research in various scientific fields
- ■ IoT applications
- ■ Sensing in general
- ■ Mobile robots, automatic vehicle guidance, collision avoidance

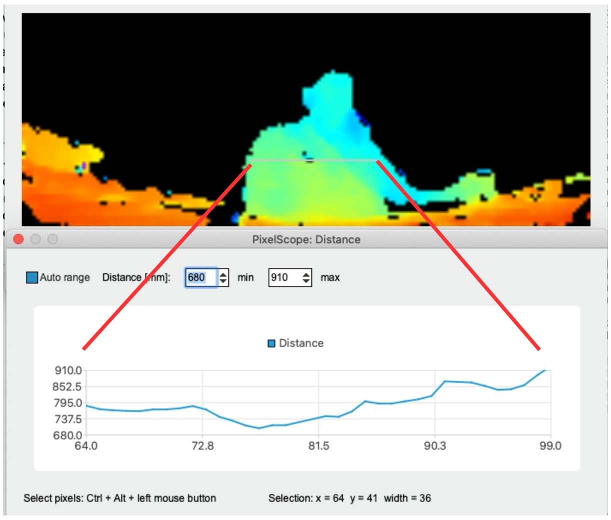


Figure 3: Distance scope for pixel row selection

Contents

1. Before you start

1.1. Precaution and Safety

	This product is eye safe according to IEC62471-2013.
	The camera module is an electronic device. Handle it with the necessary ESD precaution.
	Over-voltage: Use only a power supply which correspond to the datasheet of the camera to avoid damage of the device or cause danger for humans.
	Cable-tripping: Place or mount the sensor on solid ground or fix it correctly on a solid support. Place cables carefully. Falling devices can be damaged or harm persons.
	The camera comes with its own calibrated TOFCOS. Do not alter the TOFCOS without obeying the instructions herein.
	Be careful to the window surfaces of the camera. Never use any solvents, cleaners or mechanically abrasive towels or high pressure water to clean the sensor.
	Operate the device in compliance with the local EMC regulations.
	This camera is not a safety device. It may not be used in safety applications, explosive atmospheres or in radioactive environment, except the user implements the required safety measures, e.g. by redundancy. However, the sole responsibility for the safety of the application is by the user.
	LIMITED WARRANTY - LOSS OF WARRANTY This camera should only be installed and used by authorized persons. All instructions in this datasheet and in the related documents shall be followed and fully complied with. In addition, the installer and user is required to comply with all local laws and regulations. The installer and user is fully responsible for the safe use and operation of the system. It is the sole responsibility of the installer and the user to ensure that this product is used according to all applicable codes and standards, in order to ensure safe operation of the whole application. Any alteration to the devices by the buyer, installer or user may result in device damage or unsafe operating conditions. ESPROS Photonics AG is not responsible for any liability or warranty claim which results from such manipulation or disregarding of given operating instructions.
epc espros photonics corporation	ESPROS Photonics AG is an ISO 9001: 2015 certified company.
CE RoHS	This product is according to European Union standards and free of hazardous substances.

1.2. Updates

ESPROS Photonics is constantly striving to provide comprehensive and correct product information. Therefore, please check ESPROS' website regularly for updated versions of datasheets and documentations: www.espros.com

	Download the latest Flyer TOFcam-635.
	Download the latest “Installation and Operation Manual TOFcam-635-S”.
	Download and use the latest software package “TOFCAM635-S_SW_Package” containing a graphical user interface (GUI) for Windows, Mac or Linux computers, a robot operating system (ROS) application and a Python API framework. The current firmware “TOFCOS” is part of the GUI which allows an easy upgrade of the camera with current firmware. If there are any questions, please contact your ESPROS sales office or send an email to sales@espros.com.
	Download and use the latest software development kit (SDK) “TOFCAM635-S_SDK” containing all source codes of the firmware, GUI, ROS and API. Unpacking the SDK is password protected. Get back to ESPROS to check whether you fulfill the requirements to get the password.

1.3. Important Notes

Notes on PRELIMINARY versions:

THIS MANUAL IS UNDER CONSTRUCTION. IMPORTANT PARTS MAY BE MISSING

Colored marking in text means “under consideration” and refers to not yet applicable or verified information.

Values and/or information are either estimates or show the applicable principle only.

2. Abbreviations

Designator	Description
3D	Three dimensional
ACK	Acknowledged
API	Application program interface
ADC	Analog-to-digital converter
Binning	Summation of a defined number of pixels. Binning can be done in the charge (analog) or in the digital domain
CMD	Command
CRC	Cyclic redundancy check (checksum)
DCS	Differential correlation sample
DLL	Delay locked loop, controllable delay line
DRNU	Distance response non-uniformity: Distance error from pixel to pixel with a target at the same distance
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ESD	Electrostatic discharge
FoV	Field of view
fps	Frame rate, number of images per second
Frame	One image
GND	Ground terminal, negative supply voltage
GS	Grayscale
GUI	Graphical user interface
HDR	High dynamic range
ID	Identifier
IN	Input terminal which is used to sense a high or low voltage
ISO	International organization for standardization
JEDEC	Joint electron device engineering council
LED	Light emitting diode used to illuminate the scenery or as indicator
LSB	Least significant bit / byte
LVTTL	Low voltage transistor transistor logic
MSB	Most significant bit / byte
NACK	Not acknowledged
OUT	Output terminal which is can be set to high or low voltage
RMS	Root mean square
RoHS	Restriction of hazardous substances
ROI	Region of interest in the pixel-field
ROS	Robot operating system
RX	Receive terminal, data in
SW	Software
TBD / tbd	To be defined, information not yet available or not valid
TOF	Time of flight
TOFCOS	TOF camera operating system, firmware in the camera
TTL	Transistor transistor logic
TX	Transmit terminal, data out
UART	Universal asynchronous receiver transmitter
USB	Universal Serial Bus
VDD	Positive supply voltage

Table 1: List of abbreviations used in this document

3. Quick guide

3.1. Connecting the camera module

First of all you need to prepare a power supply to supply the camera with power. Therefore use the 8 pin connector which is included in the scope of delivery. If you ordered the power supply and power adapter cable as accessory according to Chapter 4.3 then you don't need to provide a separate power supply connected to this 8 pin connector.

You need to install the Graphical User Interface onto your computer. This is available with the "TOFCAM635_SW_Package" from our download page.

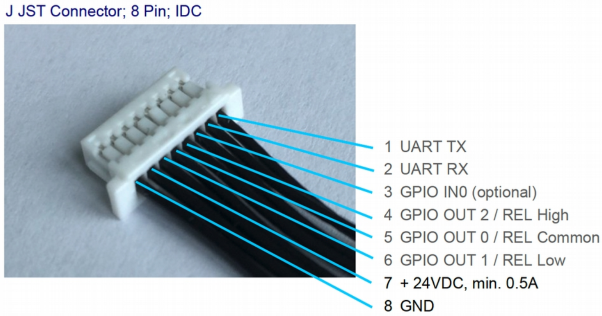


Figure 4: 8-pin power-supply , UART and GPIO connector

- Connect the camera to your computer with a USB cable.
- Connect the camera to proper voltage using the prepared or ordered power supply.
- Start the GUI on your Computer. The connection to the camera will be indicated in the corner bottom left of the main window of the GUI (Connected).

3.2. Camera settings

- Choose Image Type "Distance"
- Disable “Automatic Integration Time 3D” and switch “HDR off”
- Set “Offset” and “Distance Min” values to zero and the "Distance Max" to the effective maximum distance in your scenery.
- For object detection set the "Amplitude" limit 0” to 50 LSB, for accurate measuring to 200 LSB (this are good starting points, fine-tuning possible). Start streaming with the “Start” button.
- Increase / decrease the "Integration Time 3D 0" to a value where you get a distance picture of the most far objects you would like to see.
- Swith to “HDR temporal” and set “Integration Time 1 … 3” to zero. increase the "Integration time 3D 1" to a value where saturation (purple), ADC overflow (pink) and invalid (black) pixels are removed or reduced to a minimum (normally this value is about 10 ... 20% of the "Integration time 3D 0" value).
- Play with filtering: enable "Temporal Filter" e.g.
- Optimize the color scale (visual graduation) of the relevant objects in your scenery by changing the "Distance Range min." value.
- Change the image type to the illustration of the scenery you like to see.
- Swith on the additional “Info” and “Scope” windows which delivers you valuable information.

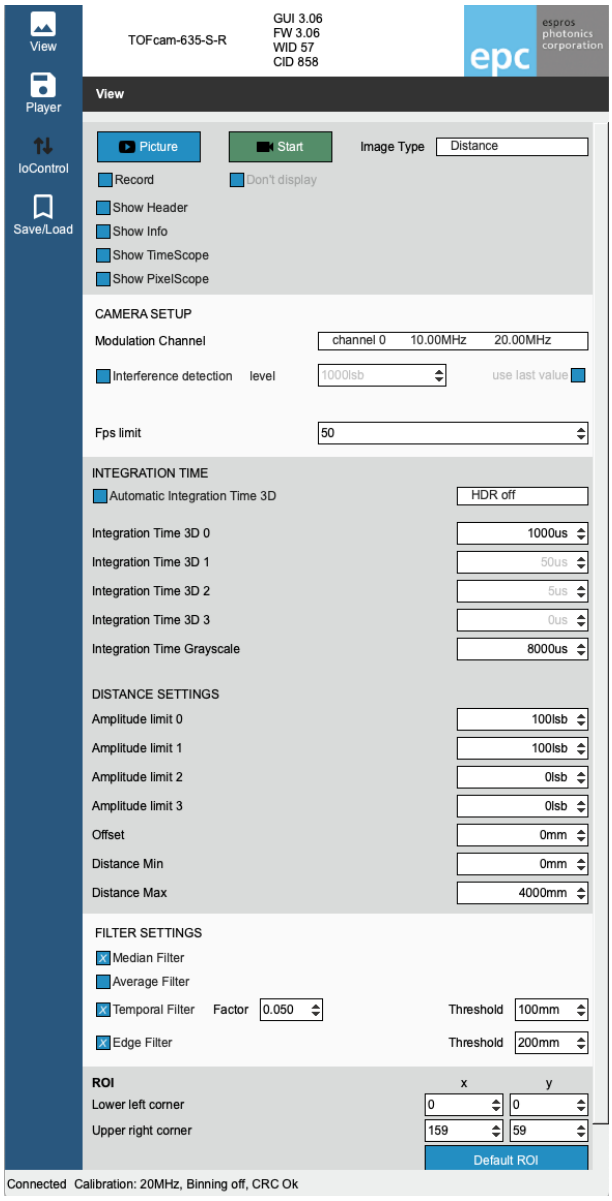


Figure 5: GUI window for camera settings

4. TOFcam-635-S time of flight camera module

4.1. System overview and use cases

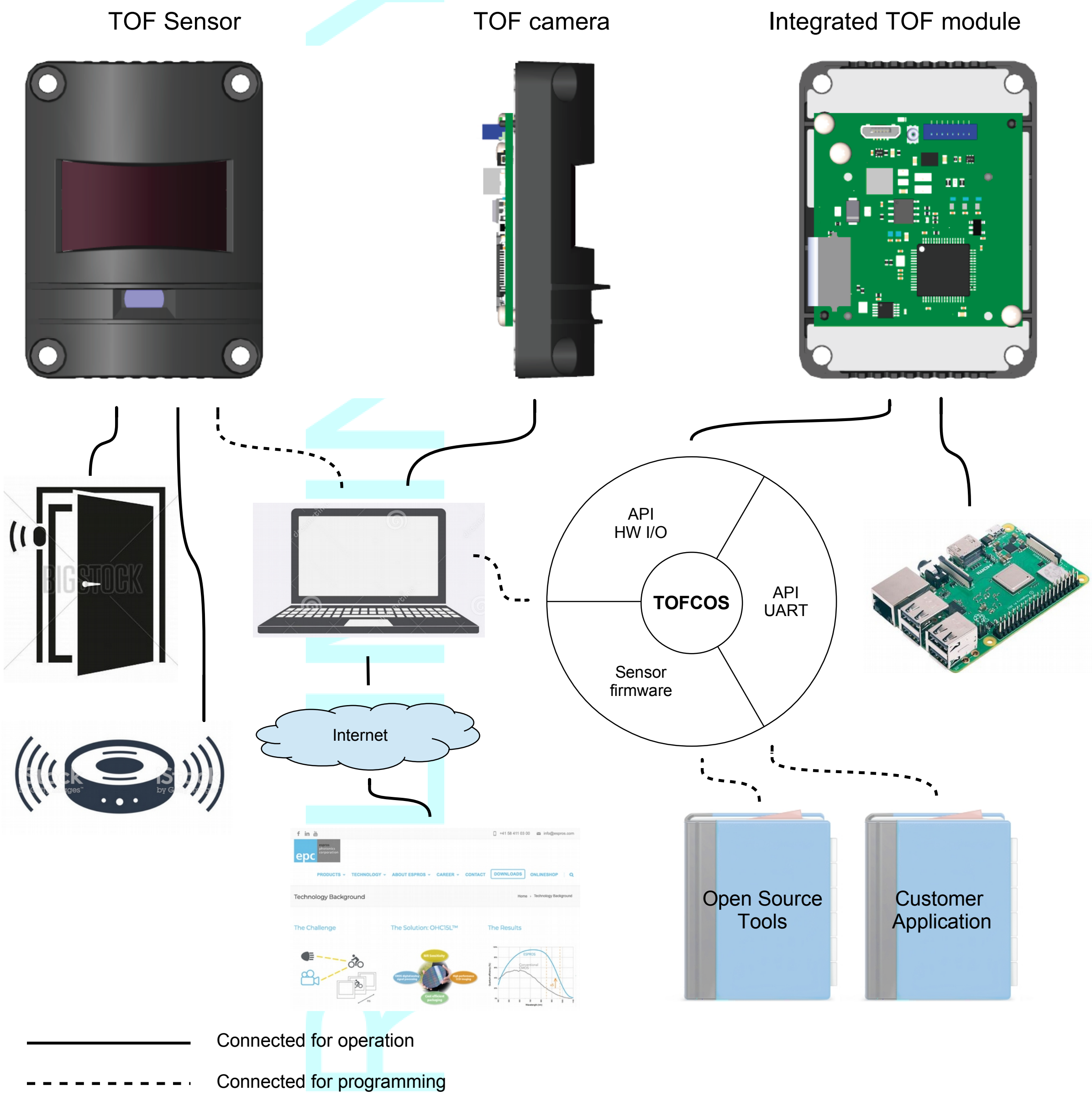


Figure 6: Use case overview

The TOFcam-635-S is a camera and sensor module based on the ESPROS epc635 cwTOF imager chip:

- 24VDC power supply input
- STM32F466 ARM microcontroller
- The micro controller board communicates with the epc635 chip carrier board through an ultrafast TCMI serial interface.
- An ultra wide field lens focus the reflected light from the scenery onto the pixel field of the imager chip
- NIR band pass filter, AR coatings and straylight suppression for optimal optical performance
- LED illumination
- TOF camera operating system (TOFCOS) for camera control, distance calculation and filtering
- Two sensor versions are available with one relay or three digital outputs
- Communication by USB or UART
- Application programming interface (API) for further processing is available. It opens the world for using open source tools or creating own customer applications.
- ROS device drivers for Linux available
- Windows, Mac and Linux GUI available

4.2. Scope of delivery

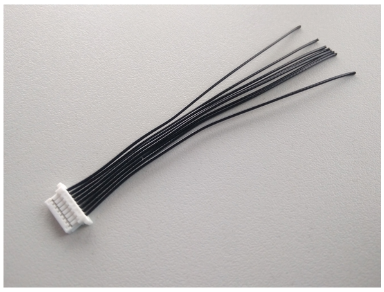
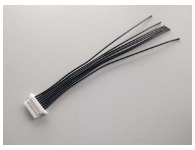
Pieces	Part Name	Picture
1	Time of Flight Sensor TOFcam-635-S consisting of: – Molded housing – Receiver lens – Illumination with lens – Electronics board	
1	8 pin connector plug with L = 75mm open end cable for 24V power supply, UART interface and GPIO – Plug with 8 pin open cable ends – Connecting instructions – Pin assignment	
1	Software package containing GUI, ROS, Python API and current Firmware. Available on the ESPROS download page.	
1	Documentation (useful additional information available on the Espros download page)	

Table 2: Scope of delivery

4.3. Ordering information

Picture	Part No.	Name	Description
	P100 651	TOFcam-635-S-UWF-850-E	Camera with 1x digital input and 3x digital output (0 … 24V)
	P100 623	TOFcam-635-S-UWF-850-R	Camera with 1x digital input and 1x relay output NO/NC
	P100 664	8 pin connector plug with open cable ends (L = 75mm)	Included in TOFcam-635-S basic unit. To connect the camera to a corresponding power supply.
	P100 660	Power supply 24VDC	Input 100 … 240VAC, 50 / 60Hz Output 24VDC, 500mA Including camera connection cable

	P300 189	Power cord adapter CH/EU – US	
	P300 473	Cable USB A to Micro USB	

Table 3: Order information for cameras and accessories

4.4. Technical data

All characteristics are at typical operational ratings, T_A = +25°C, V_{DD} / V_{DDLED} = 5V, object reflectivity 90%, unless otherwise stated.

Parameter	Description	Conditions	Min.	Type	Max.	Units	Comments
V_{DD}	Main supply voltage	Ripple [1] < 50 mV_{pp}	4.75	5.0	5.25	V	
I_{DD}	Main supply current	Acquisition		140		mA	
		Idle		100		mA	
λ	Operating wavelength			850		nm	
RES_{IMAGE}	Image resolution			160 x 60		Pixel	
FOV	Field of view	TOF FOV		120 x 25		°	160 x 35 pixels
		GS FOV		120 x 45		°	160 x 60 pixels
D	Operating range		0.05		3	m	Depends on integration time
$D_{Unabiguity}$	Unambiguity range [2]		7.25	7.5	7.8	m	Depends on mudulation channel
Acc	Accuracy	0.05 … 1.0 m		± 2		cm	Mean of 100 samples
		1.0 … 3.0 m		± 2		%	
D_{NOISE}	Distance noise (1σ value)			0.1		mm	Amplitude 100 ... 1'900 LSB, Kalman Filter k = 10 and threshold t = 300 mm, ambient-light less than 10 kLux on target
t_{INT}	Integration time selectable		1		1000	µs	Default: 125µs
t_{CYCLE}	Measurement cycle time	GET_DIST GET_DIST_AMPLITUDE		50 72		ms ms	@t_{INT} = 125µs, single measurement, including data transmission
f_{MOD}	Modulation frequency		19.20	20.00	20.70	MHz	Refer to Chapter 8.4.1
t_{PWR_UP}	Power up time until acceptance of commands				1.5	s	
t_{WARM_UP}	Warm-up time until output data is in tolerance			Refer to Chapter 8.5.4			
$RES_{DISTANCE}$	Distance measurement resolution			1		mm/LSB	Refer to Chapter 8.5.
Φ_{AL}	Ambient-light suppression			100		kLux	Indirect, on target
$E_{e\ PEAK}$	Peak illumination irradiance				372	W/m²	With 200mm distance to the front surface of the camera
$E_{e\ AVG}$	Average illumination irradiance			108		W/m²	With 200mm distance to the front surface of the camera
V_{OUT}	OUT0 / OUT1 / OUT2 voltage (open drain)				36	V	Refer to Figure 24
I_{OUT}	OUT0 / OUT1 / OUT2 current sink				50	mA	Over-current protected
V_{REL}	Relay voltage				30 125	VDC VAC	Refer to Figure 26
I_{REL}	Relay current				1 3	A A	DC AC
V_{IN}	IN input voltage	logic low	0		0.8	V	Input resistance 100kΩ, refer to Figure 25
		logic high	3.0		30	V	
T_A	Ambient temperature range		-20		60	°C	Operation and storage
RH	Relative humidity		15		90	%	Non-condensing
W	Weight			43		g	Without cable
ESD	Electrostatic discharge rating			JEDEC HBM class 1C (1kV to < 2kV)			Human body model
EMC / EMI	EMC emission			EN 61000-6-3:2011, EN 61000-6-2:2005			
	Eye safety			IEC62471:2013			

Table 4: Technical data

Notes: I

1. Min. and Max. voltage values include noise and ripple voltage
2. The camera uses the continuous-wave TOF phase-shift measurement technique with a modulation frequency 20MHz. This leads to unambiguity distances of 7.5m. Highly reflective objects outside of the effective operating range of 7.5m will appear closer due to the wrap-around of the modulation period. Example: Is the object at a distance of 8.5m, the camera displays a distance of 1m (8.5m - 7.5m). This is obviously wrong !

4.5. Mechanical data

4.5.1. Mechanical features

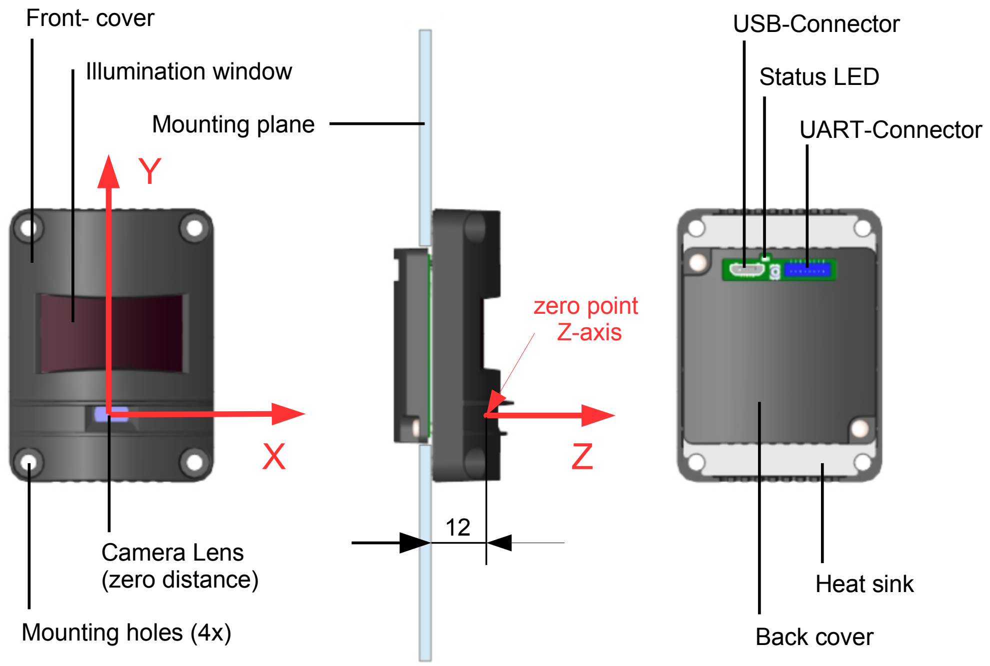


Figure 7: Mechanical features

4.5.2. Mechanical dimensions

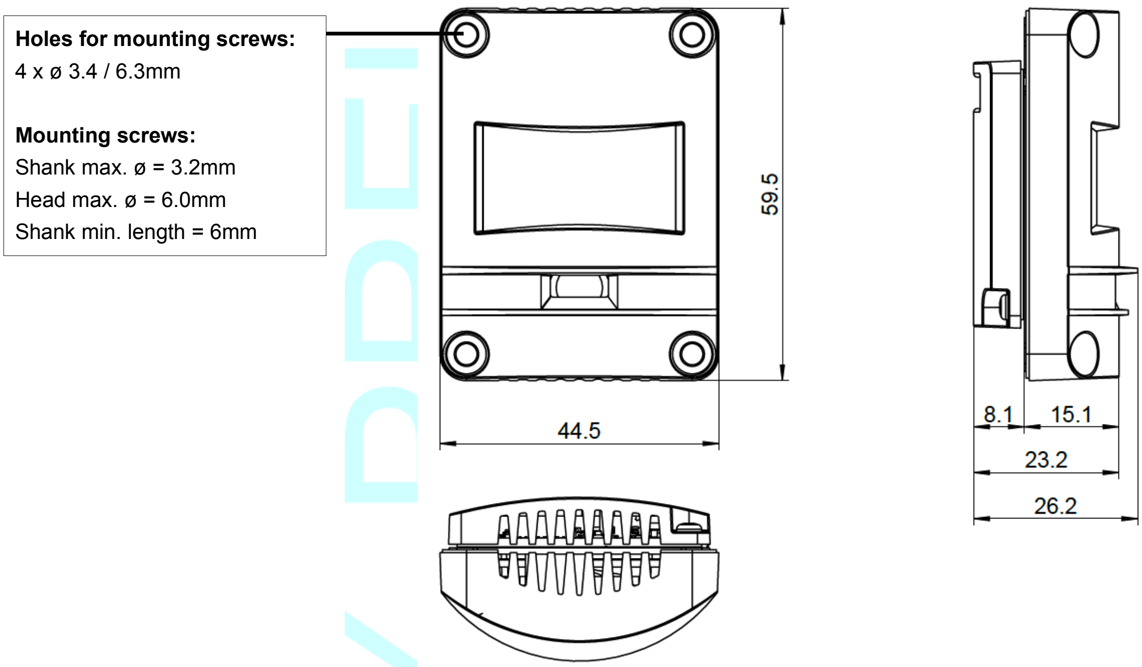


Figure 8: Mechanical dimensions

4.5.3. Mounting plane

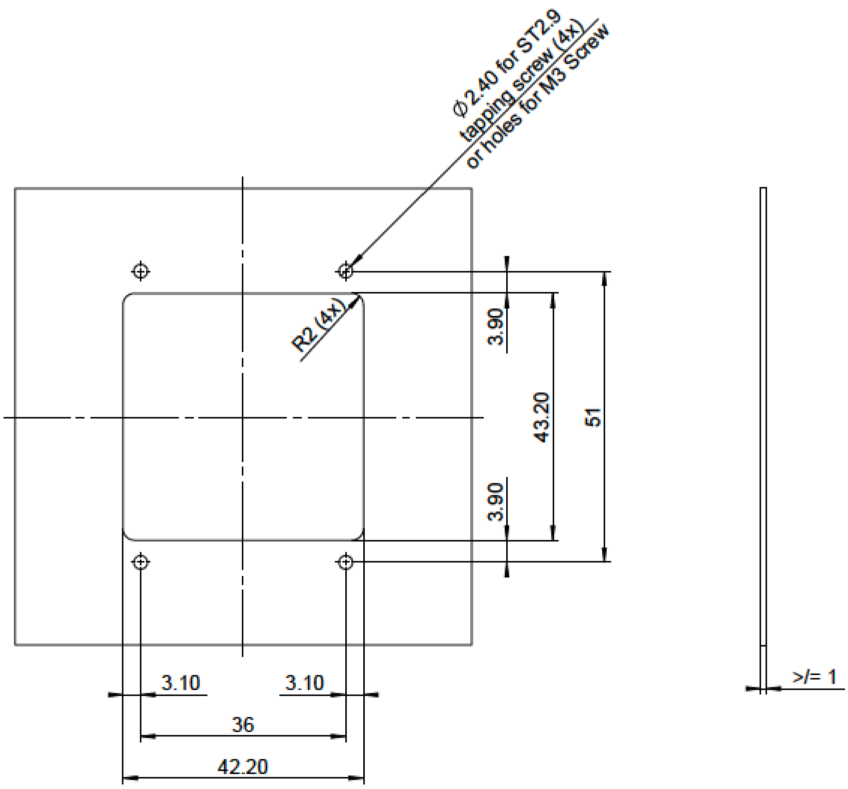


Figure 9: Hole pattern for mounting the TOFcam-635-S

Notes:

- Because the mounting plate is also a heat sink for the illumination LEDs, it should not be covered by thermal insulating material. Free air flow shall be provided at any time in order to avoid excessive heat of the camera. The camera temperature can be monitored by reading the temperature with the command GET_TEMPERATURE (refer to Chapter 8.6.3).

5. GUI

5.1. Put the camera into operation

Connect the camera to 24V DC using the 8 pin UART interface connector with a suitable 24V power supply according to Chapter 4.3. The status LED is flashing with 0.5Hz after correct power up of the TOFcam-635-S.

5.1.1. USB interface

Connect the camera with your computer using a USB-A to micro-USB cable. So you can control the TOFcam-635-S using the GUI or ROS. Start the GUI or ROS to run the camera application. If multiple cameras are physically connected to your computer, select the one you would like to operate.

5.1.2. UART interface

Connecting the required pins for UART interface and optionally the GPIO / relay contacts allows the integration of the sensor to a controller. You will find a description of the interface in Chapter 8.1 and the applicable commands in Chapter 8.2.

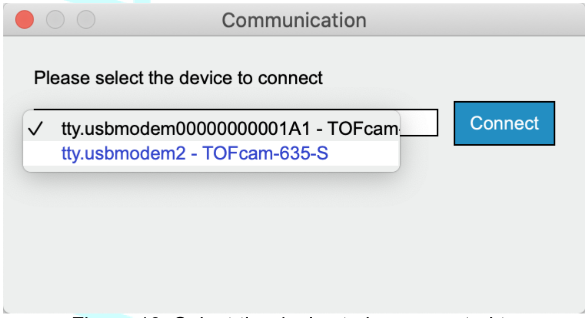


Figure 10: Select the device to be connected to

5.2. GUI main window

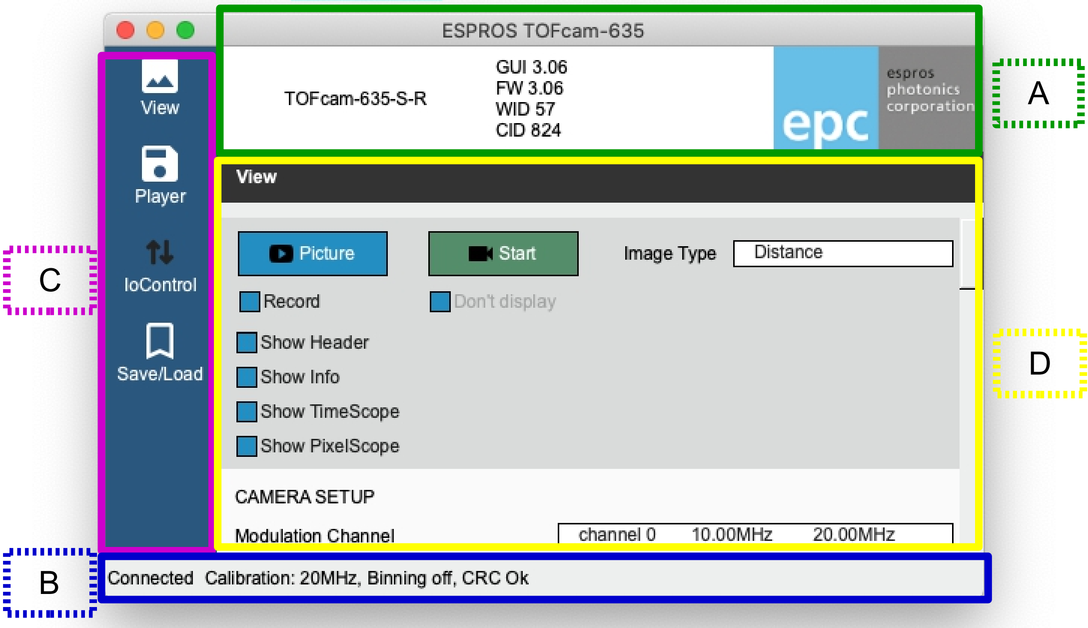


Figure 11: Sections of the GUI main screen

A) Icamera type, GUI version, Firmware version, Chip-/Wafer-ID of the epc635 in the camera

B) Connection status:

C) Menu tab

View	Chapter 5.2.1
Play	Chapter 5.2.2
IoControl	Chapter 5.2.5
Save/Load	Chapter 5.2.6

D) Controls for the selected menu tab

5.2.1. View Menu

The View menu allows to control the camera and the camera output. Distance, amplitude and gray-scale images can be captured, streamed or recorded. Detailed information about pixel groups or one single pixel can be illustrated.

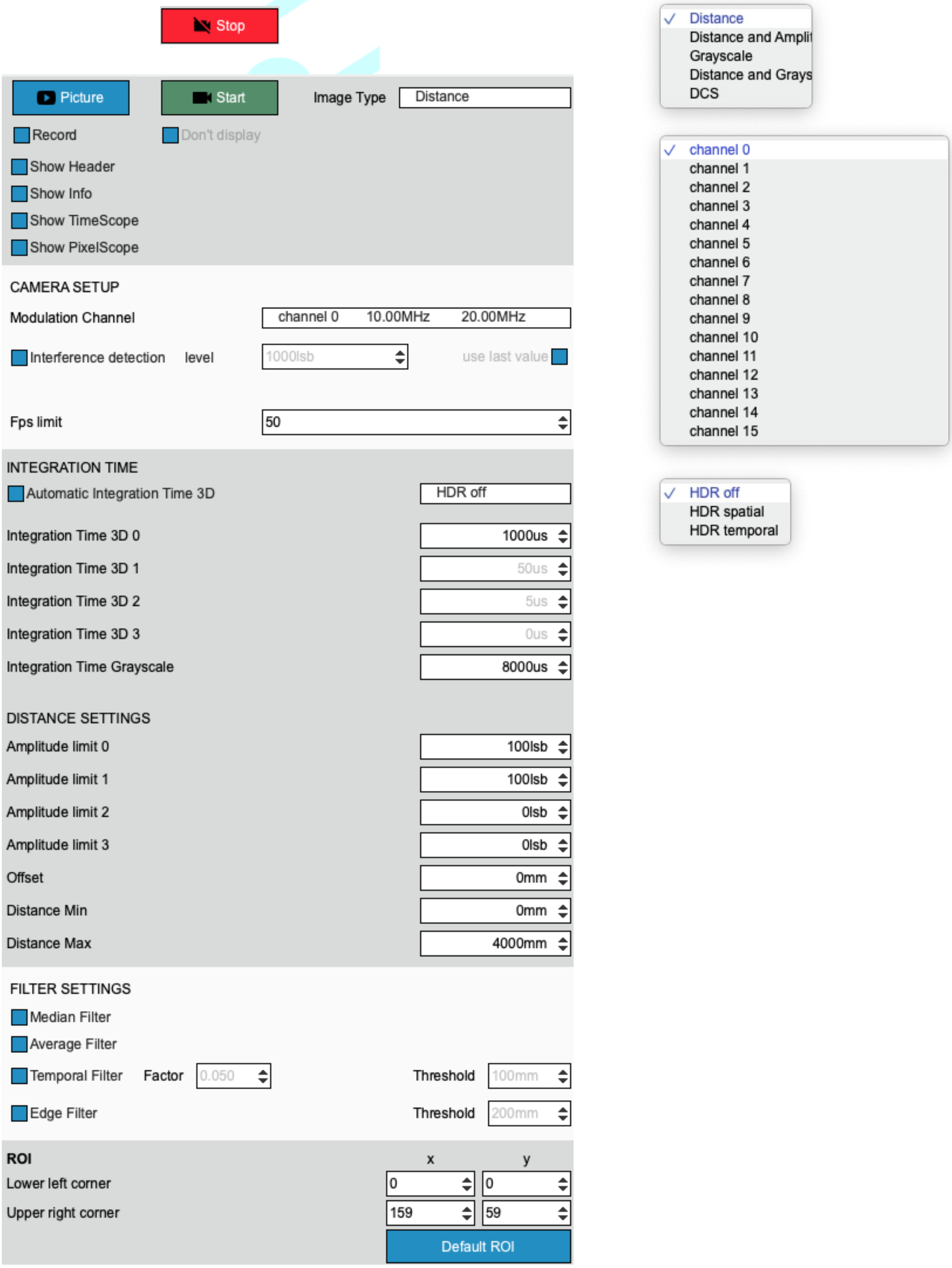


Figure 12: Controls of the camera

- “Picture“ and “Start“ open the “Image“ window according to the selection in the “Image Type” drop-down menu. Please see Chapter 5.2.3 to read the details about the live image window. The “Picture“ button acquires one single frame while the “Start“ button starts a live stream. It changes its look to “Stop“ which allows terminating the streaming.
- “Record“ function allows to save picture data (one picture per push on the “Image“ button) or as live stream (from “Start“ to “Stop“ command each). On computers with low performance it might be helpful to enable the “Don't display” function to use all resources for recording the live stream. The recorded data contains all values according to the selected “Image Type“.
- All the “Show ___“ check boxes open additional windows with dedicated information. You will find additional description about these functions in Chapter 5.2.4.

- “Modulation channel” allows a shift of the modulation frequency to the main (default) modulation frequency. Multiple cameras operating in the same scenery (full or partially) with the same modulation frequency will interfere each other which leads to sporadically wrong distance information. This can be eliminated if the cameras do nit use the same modulation frequency.
- To avoid interference issues due to unknown systems disturbing the sensor a “Interference detection“ can be enabled. Interfered pixels will be detected automatically and indicated as “invalid data”. By selecting the “use last value“ function the last valid value is sent for the affected pixel instead of marking it as invalid. This function is also be used to suppress motion blur.
- The “Frame rate limit” can be used to limit the frame rate. The function is active only if the set value is below the maximum frame rate according to all set camera parameters. The maximum operating frame rate can be displayed in the “Show Info“ window. The frame rate limit is be useful if a defined frame rate is required. It is also useful to limit the power consumption and/or power dissipation of the camera. This could happen due to very high frame rate at small ROI.
- Integration time setting allows to define the exposure time to acquire one Differential correlation sample (DCS). Four DCS' are required for distance acquisition.
- “HDR off“ let's the camera operate with one integration time only.
- “HDR spatial“ operates all odd rows of the imager with the “Integration Time 3D 0“ value and all even rows with the “Integration Time 3D 1“ value.
- “HDR temporal“ allows using up to 4 different integration time values (integration time values with zero values are ignored). In this mode one complete image is acquired with each set integration time 3D 0 … 3. After the acquisition of all frames, a new image is generated from the different frames by using the most confident value (pixel by pixel)l. Due to multiple image acquisi-tions, this mode reduces the frame rate.
- For each integration time, a minimal amplitude can be set. This is the minimum received signal to provide distance. One should use low limits for object recognition but high limits for accurate distance measurements. Please investigate the TOF theory to become familiar with the physical context. A very helpful lecture might be the book “3D-TOF, A guideline to 3D-TOF sensors that work” by ESPROS Photonics Corp. (author Beat Dede Coi et. al.).
- “Offset“ shifts the zero distance from its original z-axis zero point (refer to Figure 7).
- “Minimum distance“ cuts off all pixels reporting a value closer than this setting. In addition, the color distance scale is adjusted this setting.
- “Maximum distance“ cuts off all pixels reporting a value beyond this setting. In addition, the color distance scale is adjusted this setting.
- The color scale visualizes distance of every pixel in the viewer.
- Various powerful filter functions are available.
- The ROI (region of interest) allows to reduce the active pixel field. Only pixels within the selected ROI will be acquired. The “Default ROI” button resets the ROI to full imager size of 160 x 60 pixels.
- Tooltips are available by moving the cursor either to the corresponding text (refer toFigure 13).

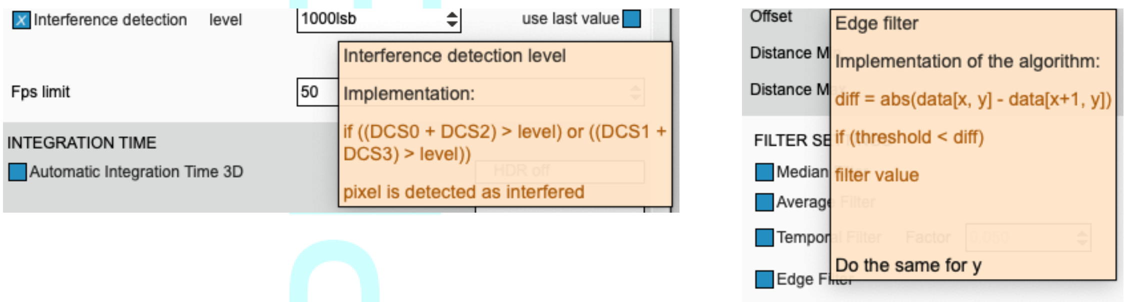


Figure 13: Tooltip examples

5.2.2. Play menu

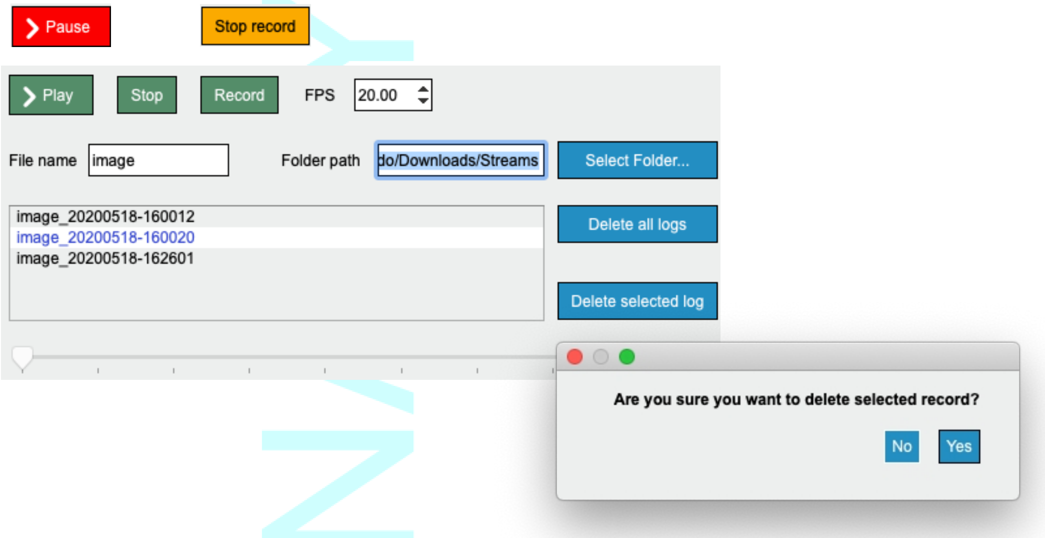


Figure 14: Player controls

- “Play” replays the selected stream with the set frame rate. After changing the selection or pushing the “Stop“ button the original frame rate of the recording is used. The “Start“ button changes its look to “Pause“ after been pushed. Selecting the “Pause“ button interrupts the playback and allows to continue from the same point.

  The player can replay the recorded data only with the parameters which has been set during the recording process. This includes also the “Image Type“ according to the “View“ menu.
- “Stop“ aborts the replay, resets the timer to zero and the frame rate to the recording frame rate.
- “Record“ streams images according to the parameters set in the “View” menu, refer to Chapter 5.2.1.
- “FPS” sets the acquisition frame rate (or the replay speed respectively). This value is reset by pressing the “Stop“ button or by changing the selected log in the list.
- “File name“ defines the file name of the log file. An “underline” character separates this name from the current calendar day followed by a “minus” separated time stamp.
- “Folder path” defines the log file location. It path can be changed either directly in the input field or with the “Select Folder” function.
- “Delete all logs“ will delete all logs in the selected folder. “Delete selected log“ deletes the selected log only. All deletions needs to be confirmed by the user.

5.2.3. Live image window

The “Image” window pops-up after a streaming, a replay or a recording has been started from the “View“ or the “Play“ menu. The window contains the images according to the selected “Image Type“. A recorded streaming contains only the data which has been selected during the recording process.

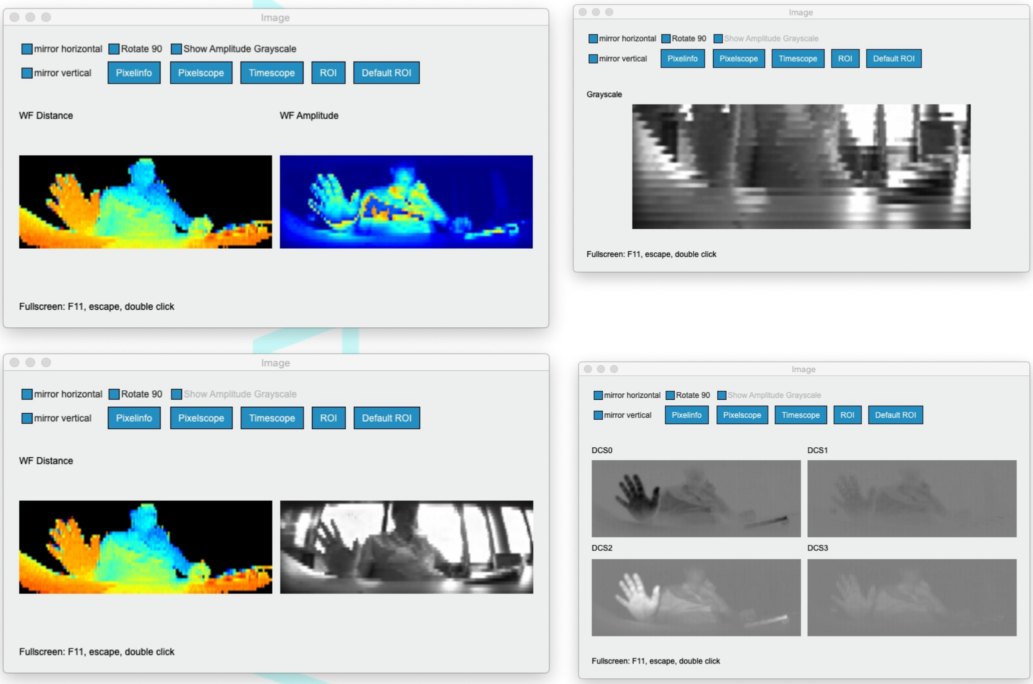


Figure 15: Image types: Distance, Amplitude, Grayscale, DCS

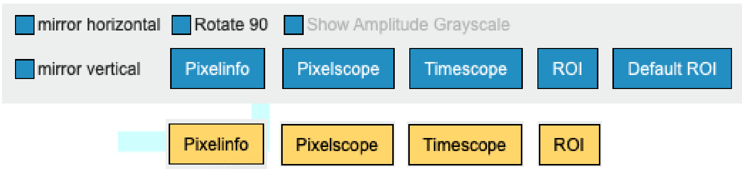


Figure 16: Live view controls

- “Mirror horizontal“ flips the image horizontally.
- “Mirror vertical“ flips the image vertically.
- “Rotate 90°” rotates the image.
- The amplitude can be shown as color coded values (default) or as gray-scale.
- The scope functions allow to show some decided information about one single pixel or a selection of many pixels. A description about these information can be found in Chapter 5.2.4. The pixel selection can be deleted with right mouse click or by just doing a new selection.
    - “Pixelinfo“ allows to select a single pixel in the active live image by left mouse click. Current information about this pixel are shown in the decided information window (Figure 18).
    - “Pixelscope“ shows the distance and amplitude values of a row of pixels (Figure 19).
    - “Timescope“ shows a selection of an ROI in the live image. The ROI is defined with left mouse button. The average of distance and amplitude values over all selected pixels are shown against time axis (Figure 20).
- “ROI“ selects a region of interest by using the left mouse buton. “Default ROI“ resets the ROI.

5.2.4. Decided information windows

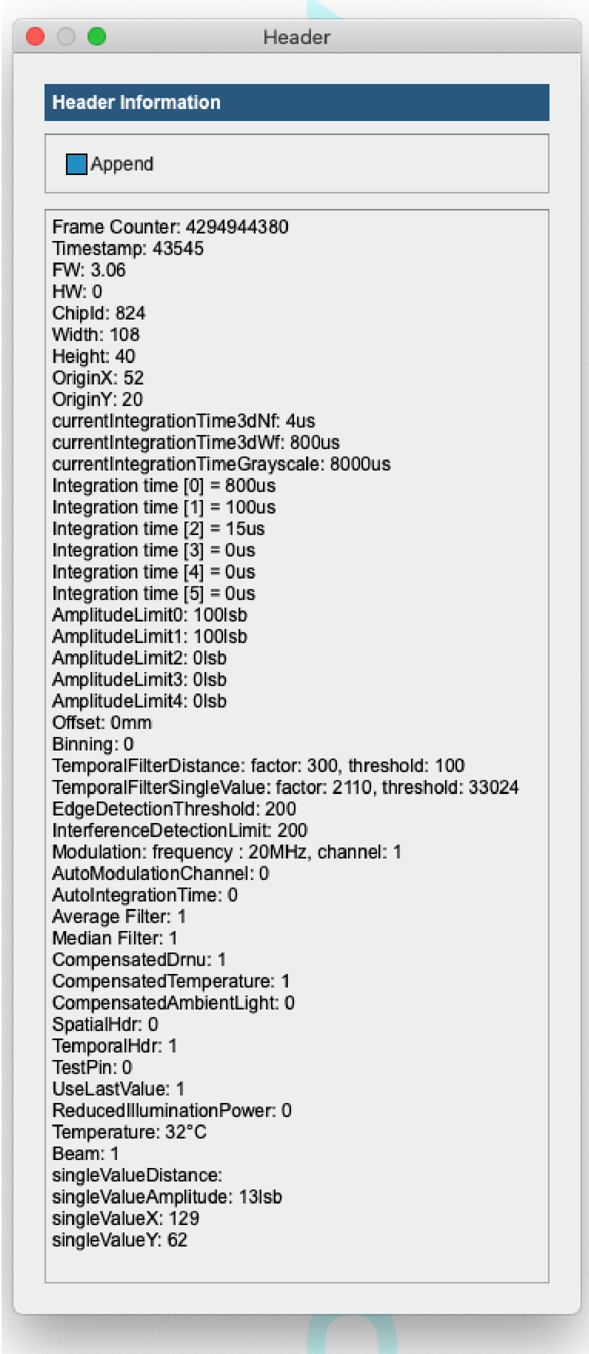


Figure 17: Header information window

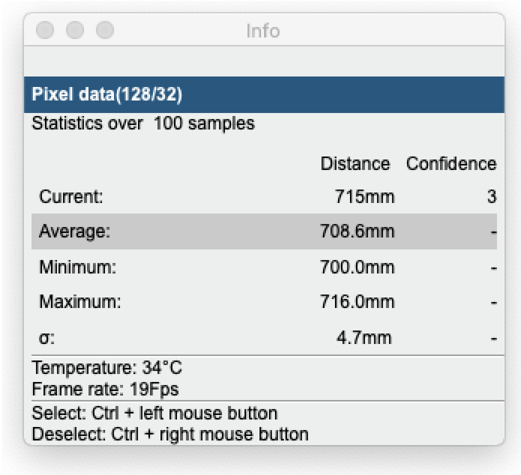


Figure 18: Pixel information window

If the “Append“ check box is activated in the “Header information“ window the data for each single frame are added to the file. If it is disabled just the data from last frame are stored.

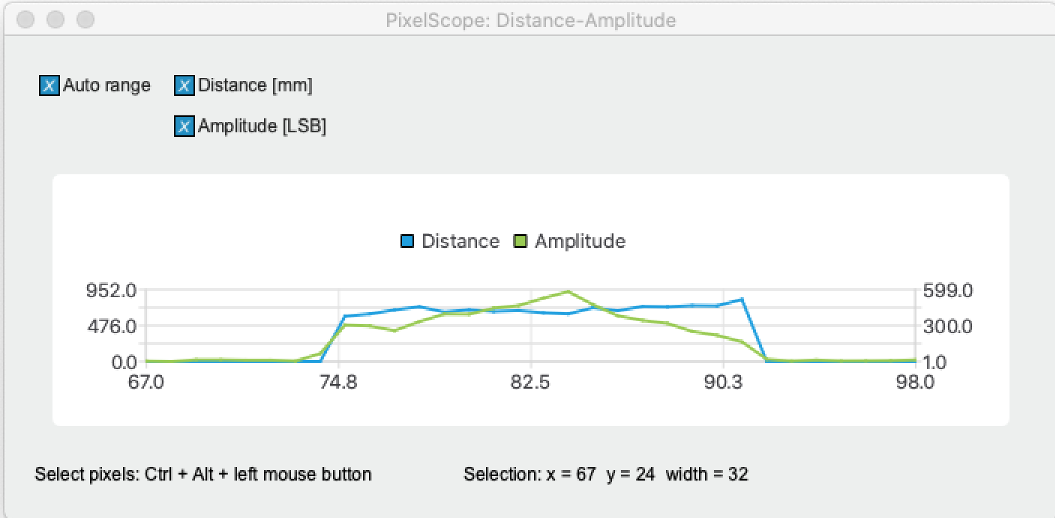


Figure 19: PixelScope window

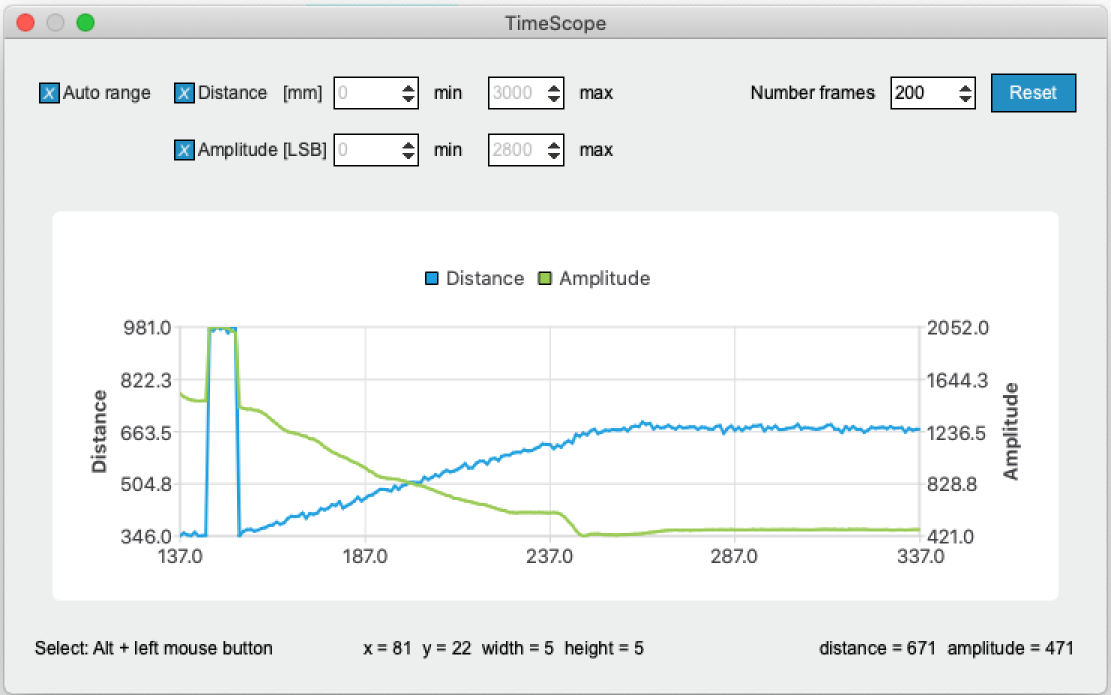


Figure 20: Time Scope window

Number of frames can be used to compress or stretch time axis. With the “Reset“ function the current data can be deleted.

5.2.5. Input readout and Output Control menu

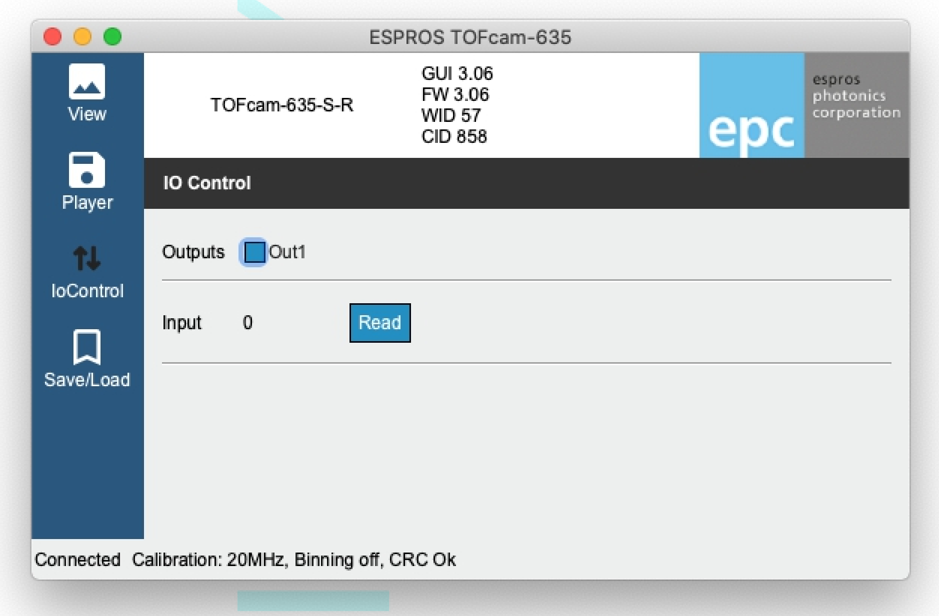


Figure 21: IO control window

The Output check-boxes allow to manually set an output, the “Read” button detects the Input status. For the corresponding pinning please see 3.1.

5.2.6. Configurations and firmware upgrade menu

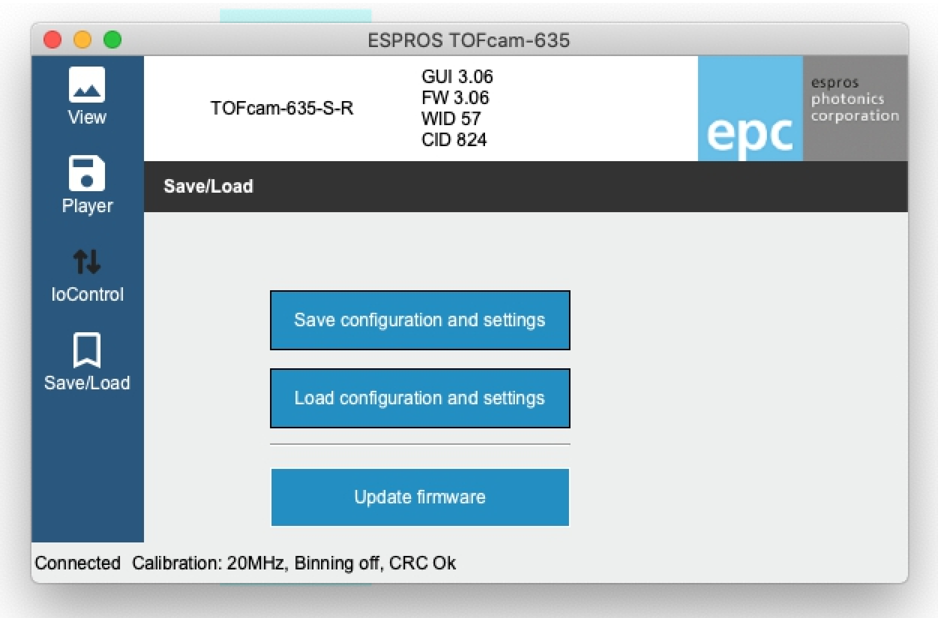


Figure 22: Configurations and Upgrade window

“Save configuration and settings“ to the PC.
“Load configuration and settings“ from the PC.
“Update firmware“ allows to download a mew or different firmware to the camera.

6. Operating the device with a ROS

6.1. ROS camera driver

6.1.1. What is ROS?

The Robot Operating System (ROS) is a set of software libraries and tools that help you build robot applications. From drivers to state-of-the-art algorithms and with powerful developer tools, ROS has what is needed for a robotics project. It is all open source (Source: ROS.org). For more details, also refer to ROS.org and ROS Wiki sensors.

6.1.2. Installation

System requirement: Linux operating system.

Download the “TOFCAM635_SW_Package” from the website www.espros.com, section Downloads, 02_Cameras_and_Modules.

There is enclosed the “TOFCAM635_ROS_driver” file. Unpack this ZIP file.

6.1.3. Running the ROS driver

Change to the home directory and open the bash-file:

```
> cd ~
> gedit .bashrc
```

Insert the following line at the end of the bash-file:

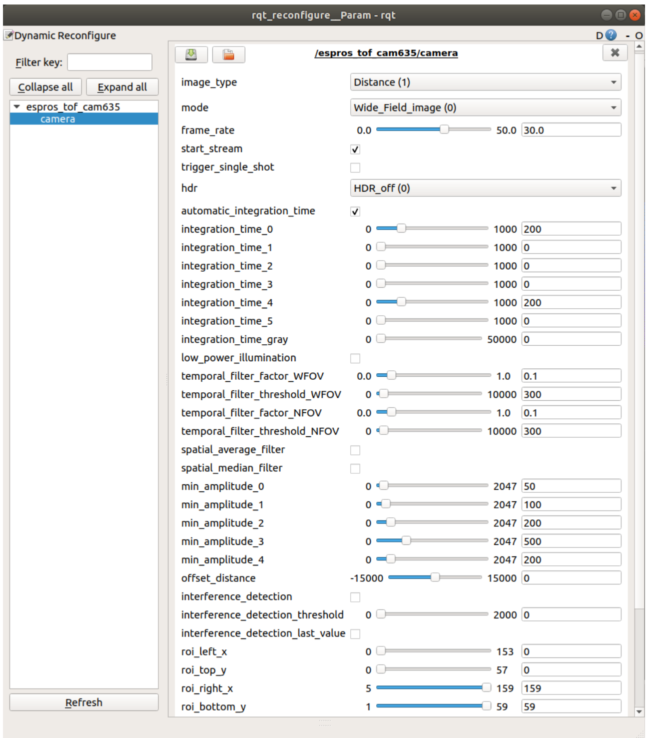
```
Source ~/NameProjectDirectory/cam635_ROS_Driver/devel/setup.bash
```

Save the file and exit editor.

Start the ROS with GUI in terminal mode with the following command:

```
roslaunch espros_tof_cam635 camera.launch
```

The ROS tool opens with the different node windows and is ready to use.



Text 1: Figure 16: Example of the “dynamic reconfigure” node window

Start the camera operation by changing in the menu the parameter “start_stream” from false to true.

6.2. ROS API

This is the official driver for the ESPROS TOFcam635. The annotation follows the rules of ROS.org.

6.2.1. Start of the node

If you use in terminal mode the APIs only, without GUI:
Start the ROS operating system in a Terminal1 with the command: `roscore`
Start the TOFcam635 in a Terminal2 with the command: `rosrun espros_tof_cam635 tof_cam635_node`

6.2.2. Published topics

Topic name	ROS msgs file	ROS message type	Function
camera/image_raw1	sensor_msgs	Image	Sends the grayscale or amplitude image according the selected image type parameter
camera/image_raw2	sensor_msgs	Image	Sends the distance image for image type parameters which include distance
camera/imageHeader	std_msg	Int32MultiArray	Sends the image header. Refer to Table 6.

Table 5: ESPROS ROS topics

Entry	Index	Entry	Index
Header version	1	reserved2	22
Frame counter	2	AmplitudeLimit0 WFOV	23
Timestamp	3	AmplitudeLimit1 WFOV	24
TOFCOS version	4	AmplitudeLimit2 WFOV	25
Hardware version	5	AmplitudeLimit3 WFOV	26
Chip ID	6	n/a	27
Image width (x-axis)	7	n/a	29
Image height (y-axis)	8	DistanceTemporalFilter-Factor WFOV	30
Image origin X	9	DistanceTemporalFilter-Threshold WFOV	31
Image origin Y	10	n/a	32
CurrentIntegrationTime3D WFOV	11	n/a	33
n/a	12	Modulation frequency	34
CurrentIntegrationTimeGrayscale	13	Modulation channel	35
IntegrationTimeGrayscale	14	Flags	36
IntegrationTime0	15	Temperature	37
IntegrationTime1	16	n/a	38
IntegrationTime2	17	n/a	39
IntegrationTime3	18	n/a	40
n/a	19	reserved3	41
n/a	20	n/a	n/a
reserved1	21	n/a	n/a

Table 6: Header parameters (see also notes below)

Notes:

- For details and descriptions to the header parameters, refer to Chapter 8.5.3.
- ROS header bytes: In total 164 bytes. Each parameter is transmitted in corresponding 32 bit data format (Int32MultiArray).

6.2.3. Dynamically reconfigurable parameters

Refer for details on the dynamically reconfigurable parameters to the enclosed “dynamic_reconfigure package” or to http://wiki.ros.org/dynamic_reconfigure.

Detailed descriptions of the parameter's functions are listed in Chapter 5.2 and following of this document.

Parameter	Function	Data format	Default	Reference
~image_type	Sets the image acquisition type 0: Grayscale 1: Distance 2: Distance and amplitude 3: Distance and grayscale	int	1	n/a
~frame_rate	Sets image acquisition frame rate. Range 0 ... 50 frame/sec	double	30	n/a
~start_stream	Enables image streaming	bool	False	n/a
~trigger_single_shot	Starts single measurement after change from false to true	bool	False	n/a
~hdr	Sets HDR mode: 0: HDR OFF 1: HDR spatial 2: HDR temporal	int	0	n/a
~automatic_integration_time	Automatic mode: Integration time is set automatically between 1 and 1'000 µs.	bool	True	n/a
~integration_time_0	Sets the integration time for distance measurements in microseconds. Range: 1 … 4'000 µs	int	200	n/a
~integration_time_1		int	0	
~integration_time_2		int	0	
~integration_time_3		int	0	
~integration_time_gray	Sets the integration time for grayscale measurements in microseconds. Range: 0 … 50'000 µs	int	0	n/a
~temporal_filter_factor_WFOV	Sets the factor 'k' of the temporal filter (Kalman)	int	10	n/a
~temporal_filter_threshold_WFOV	Sets the threshold 'T' of the temporal filter (Kalman)	int	300	
~spatial_average_filter	Enables the spatial average filter for distance filtering	bool	False	n/a
~spatial_median_filter	Enables the spatial median filter for distance filtering	bool	False	n/a
~interference_detection	Enables interference detection	bool	False	n/a
~interference_detection_threshold	Interference detection threshold. Range: 0 … 2000 mm	int	0	n/a
~interference_detection_last_value	Enables use last detection value	bool	False	n/a
~min_amplitude_0	Sets the amplitude limits for WFOV. Range 0 … 2'047 LSB	int	50	n/a
~min_amplitude_1		int	100	
~min_amplitude_2		int	200	
~min_amplitude_3		int	500	
~offset_distance	Set distance offset. Range -15'000 … 15'000 mm	int	0	n/a
~roi_left_x	Sets the left edge of the ROI	int	0	n/a
~roi_right_x	Sets the right edge of the ROI	int	159	n/a
~roi_top_y	Sets the top edge of the ROI	int	0	n/a
~roi_bottom_y	Sets the top edge of the ROI	int	59	n/a
~lensCenterOffsetX	Lens optical axis offset relative to sensor center (x direction). Range -100 … 100 pixels.	int	0	n/a
~lensCenterOffsetY	Lens optical axis offset relative to sensor center (y direction). Range -100 … 100 pixels.	int	0	n/a
~enable_cartesian	Enables point cloud cartesian transformation (false = spheric)	bool	True	n/a
~enable_images	Activates imagePublisher1 and imagePublisher2 nodes to send information (camera/image_raw1/2)	bool	True	Table 5
~enable_image_header	Activates imageHeader node to send information (camera/imageHeader)	bool	True	Table 5

Table 7: ROS parameter table

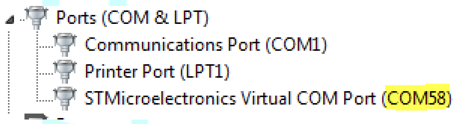
7. Operating the camera with the Python Framework

The file "SW_TofCam635_Communication_lib-v1.0" contains a Python framework with the most common commands. This framework can easily be extended according to specific requirements. Additional commands can be implemented into the "commands.py" file.

7.1. Script example

Executing the script "SW_TofCam635_Communication_lib-v1.0/Examples/TofCam635_CommunicationExample.py" in Python allows to get the first distance and amplitude data.

7.2. Comport




```
class testConnection():
  def __init__(self):
    self.tofcam635 = tofcam635.TofCam635("COM27")
```

It is required to state the correct name of the used COM-port. With Windows operating systems this name is visible in the systems manager.

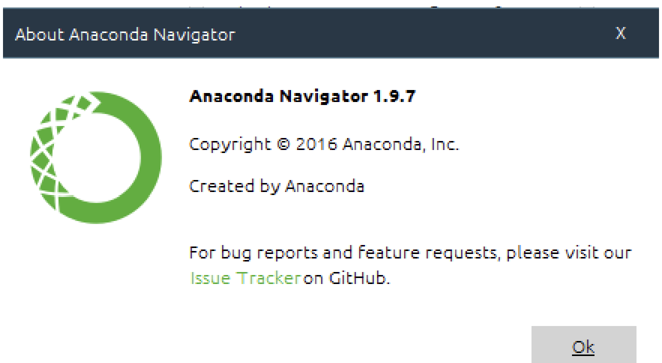
7.3. Resulting data frame

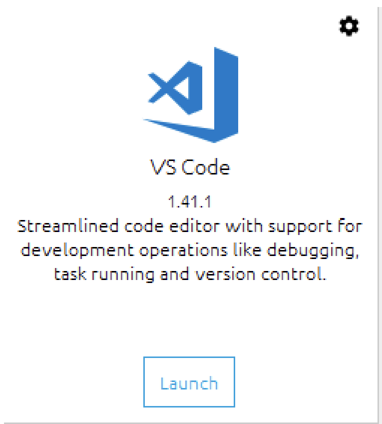
Executing the scipt example in the Python terminal delivers the information as follows:

```
Type 'copyright', 'credits' or 'license' for more information
IPython 7.4.0 -- An enhanced Interactive Python. Type '?' for help.
# Firmware Version: 3.3
# chipID:                616
# WaferID:               82
# Integration Time  0 set to:     10us
# Exponential Filter set: Threshold:   300, weight:   100
# Exponential Filter set: Threshold:   300, weight:    30
# Edge Filter set: Threshold:   300
# Interference Detection enabled, useLastValue: True, Limit:   500
TofCam635_CommunicationExample.py:48: RuntimeWarning: Mean of empty slice
  distanceMean = np.nanmean(distanceNp)
dist =    nan, temp = 25.170000, spot = -1.000000
dcs = 2055.000000, 2059.000000, 2057.000000, 2059.000000
Done
```

7.4. Toolchain:

- Python version 3.7.3 (should work with any Python3 versions)
- OS: windows, macos or linux
- Possibly some additional packages will be required. If this is the case it would be indicated by executing the script example.
- Alternatively an Anaconda-Navigater with the VS code editor can be used:





8. Operating the device by UART interface

8.1. Sensor interface

8.1.1. Connector

Connector type: JST BM08B-SRSS-TB
Matching plug: JST SHR-08V-S-B or JST SHR-08V-S
Accessory: A cable with one side plug and other side with cable leads is included in the scope of delivery.

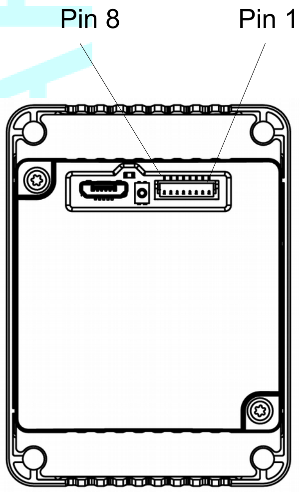


Figure 23: UART interface view

⚠ Make sure to use the right plug and insert it properly to avoid damage of the device connector!

8.1.2. Pin table for TOFcam-635-S-UWF-850-E

No.	Name	Comments
1	UART_TX	Data interface, refer to Chapter 8.2..
2	UART_RX	
3	IN	Digital input, refer to Chapter 8.6.2 and Figure 25.
4	OUT 2	Open-drain output, refer to Chapter 8.6.1and Figure 24.
5	OUT 0	
6	OUT 1	
7	GND	Negative supply terminal
8	VDD	Power supply pin +24VDC, 0.5A min

Table 8: Pin table

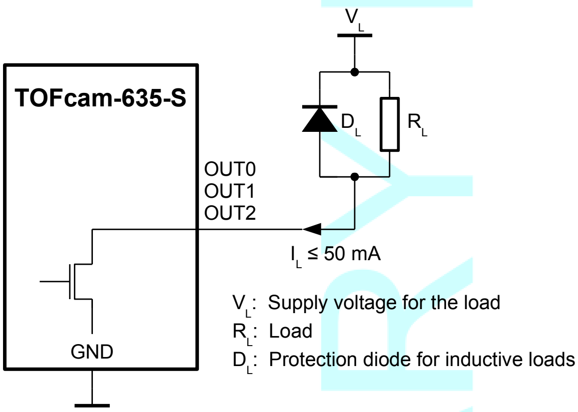


Figure 24: Schematics for OUTPUTS

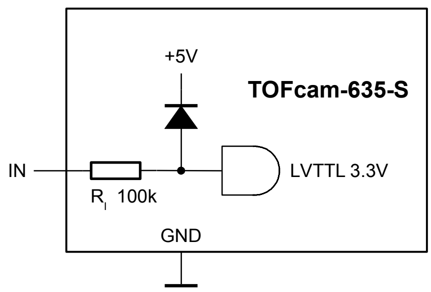


Figure 25: Schematics for INPUT

8.1.3. Pin table for TOFcam-635-S-UWF-850-R

No.	Name	Comments
1	UART_TX	Data interface, refer to Chapter 8.2..
2	UART_RX	
3	IN	Digital input, refer to Chapter 8.6.2. and Figure 25.
4	NC	Relay output, refer to Chapter 8.6.1 and Figure 26.
5	COM	
6	NO	
7	GND	Negative supply terminal
8	VDD	Power supply pin +24VDC, 0.5A min

Table 9: Pin table

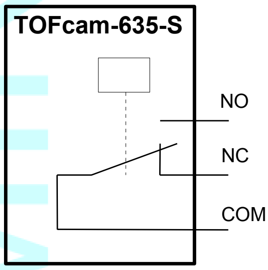


Figure 26: Schematics for RELAY

8.2. Communication interface

8.2.1. Hardware interface

Communication takes place over a standard TTL UART interface. The communication protocol is as follows:

Parameter	Value	Unit	Comment
Baud rate	10	Mbit/s	1 bit = 0.1 µs
Start bits	1	Bit	low active
Data	8	Bit	
Stop bits	1	Bit	high active
Parity	No		
Voltage level LVTTL	3.3	V	

Table 10: UART configuration

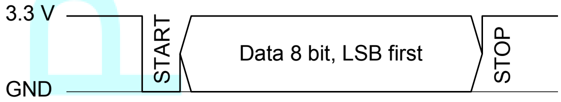


Figure 27: UART frame format

8.2.2. Software interface

The UART operates in a master-slave mode with the application as the master and the camera as the slave. A request is initiated with a command by the master. The camera as the slave returns the answer to the request after the processing time t_{PROC}. The camera does not accept commands during the processing t_{PROC} and the communication t_{COM_TX}. A next command can be issued earliest after finishing Data Out.

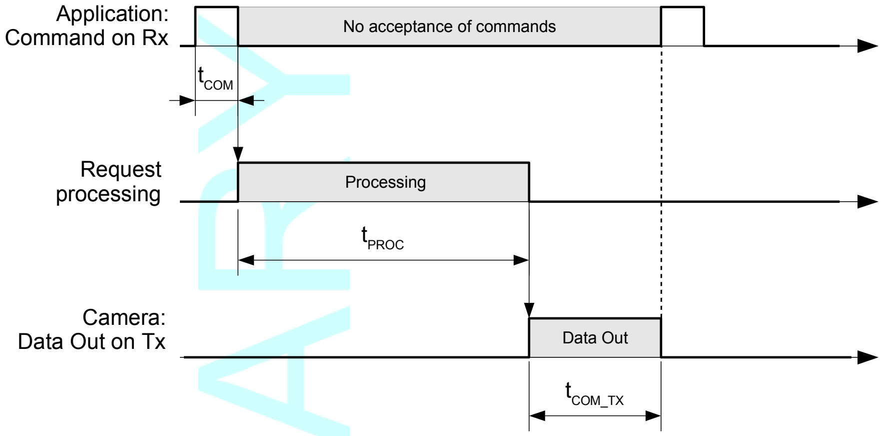


Figure 28: Command and answer sequence

Additionally, the camera has a streaming mode. The master starts the stream with a stream command. The camera continuously streams data to the master until the master stops the streaming by command. During streaming, the camera accepts commands to change parameters or to stop the stream.

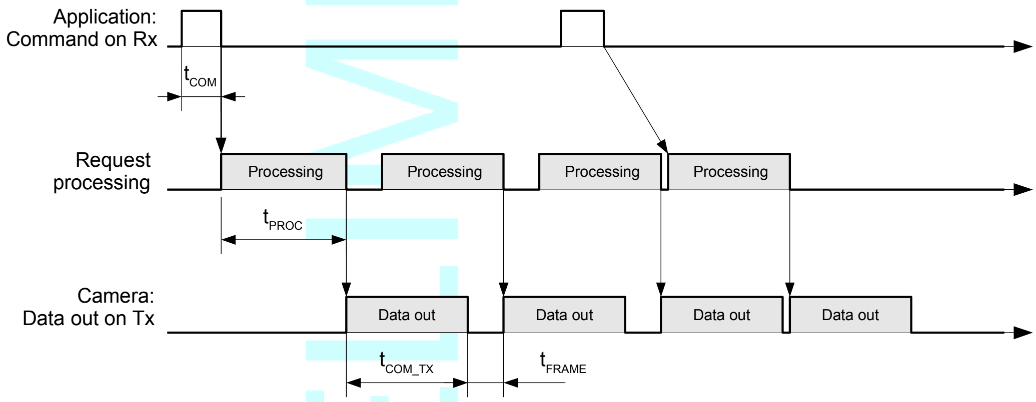


Figure 29: Streaming mode

8.2.3. Command format

The camera is operated by issuing commands on the UART interface UART_RX. The camera answers to each command with either the required data, acknowledge, not acknowledge or an error. LSB is transmitted first, MSB last.

⚠ Use the listed commands only, otherwise uncontrolled operation or TOFCOS deadlock can occur.

The command packet has a fixed length of 14 bytes: A start byte (value 0xF5), followed by 1 byte command identifier (CMD), 8 bytes of parameters corresponding to the command and 4 closing bytes with a 32bit CRC.

1 byte	1 byte	8 bytes	4 byte
0xF5	**CMD**	**Parameters, fix length**	32 bit CRC
		LSB … MSB	LSB … MSB

Figure 30: Command format

Note: Configuration settings applied by commands are stored as long as power is on or a new value is set.

8.2.4. Response format

The answer packet has variable length: A start byte (value 0xFA), followed by 1 byte type definition, 2 byte length definition n, n bytes data and 4 closing bytes with a 32bit CRC.

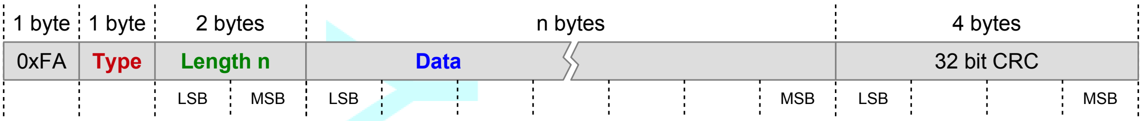


Figure 31: Response format

Note: The Readout order for pixel data starts at row 0, pixel 0 until end of row0 ... and ends with last row, last pixel.

8.2.5. CRC checksum

Data integrity is provided by a CRC checksum added to every camera response. The calculation of the CRC includes all bytes of the packet except the CRC itself. Examples are listed in the command list. The CRC specification is as follows:

- Byte-wise CRC32
- Polynomial: 0x04C11DB7
- Xor value: 0x00000000
- Init value: 0xFFFFFFFF

CRC calculation function:

```
uint32_t CrcCalc::calcCrc32_32(const uint8_t *data, const uint32_t size)
{
  uint32_t crc = initValue;
  for(uint32_t i = 0; i < size; i++)
  {
    crc = calcCrc32Uint32(crc, data[i]);
  }
  return crc ^ xorValue;
}


uint32_t CrcCalc::calcCrc32Uint32(uint32_t crc, uint32_t data)
{
  int32_t i;
  crc = crc ^ data;
  for(i=0; i<32; i++)
  {
    if (crc & 0x80000000)
    {
      crc = (crc << 1) ^ polynom;
    }
    else
    {
      crc = (crc << 1);
    }
  }
  return(crc);
}
```

8.2.6. Acknowledge ACK (response)

DATA_ACK

An acknowledge (ACK) by the camera confirms the successful processing of commands, which do not respond with a set of data e.g. such as distance (GET_DIS).

Response type 0x00: Acknowledged (ACK)

Response data 0 bytes

Response | 0xFA | **0x00** | **0x00 0x00** | (**0 bytes**) | 0xBC 0x7D 0x6A 0x77 |

8.2.7. Error handling

In case of a communication error, two special responses are implemented.

DATA_NACK

System response only: Command not accepted or unknown.

Response type 0x01: Not acknowledged

Response data 0 bytes

Response | 0xFA | **0x01** | **0x00 0x00** | (**0 bytes**) | 0xDA 0xD7 0x6A 0x85 |

DATA_ERROR

System response only: Error occurred during the execution of the command. Response instead of the required data.

Response type 0xFF: Error

Response data 2 bytes: bit 0..14: Error number. Try it again. If the error remains, contact your sales responsible.
bit 15: 0

Response e.g. | 0xFA | **0xFF** | **0x02 0x00** | **0x03 0x00** | 0xC7 0x30 0x55 0x4B | (error number 3)

8.3. Command set overview

8.3.1. SET commands

Command	CMD	Ref.	Description	Comments
SET_MOD_CHANNEL	0x0E	8.4.1.	Interference suppression parameter setting	
SET_INT_TIME_DIST	0x00	8.4.2.	Integration time for the distance measurement setting	
SET_INT_TIME_GS	0x01	8.4.3.	Integration time for grayscale measurement setting	
SET_HDR	0x0D	8.4.4.	High dynamic range mode setting (HDR)	
SET_ROI	0x02	8.4.5.	Region of interest setting (ROI)	
SET_TEMPORAL_FILTER_WFOV	0x07	8.4.6.	Temporal filter settings	
SET_AVERAGE_FILTER	0x0A	8.4.7.	Average filter settings for the distance calculation	
SET_MEDIAN_FILTER	0x0B	8.4.8.	Median filter settings for the distance calculation	
SET_FRAME_RATE	0x0C	8.4.11.	Sets the (maximal) frame rate	
SET_AMPLITUDE_LIMIT	0x09	8.4.12.	Amplitude limits settings for the confidence information	
STOP_STREAM	0x28	8.4.13.	Stops the stream from the camera	
SET_COMPENSATION	0x55	8.4.14.	Sets the compensation flags	
SET_DLL_STEP	0x06	8.4.15.	Sets the DLL step for artificial distance shift	

Table 11: SET commands

8.3.2. GET commands

Command	CMD	Ref.	Description	Comments
GET_DIST	0x20	8.5.5.	Performs distance acquisition	
GET_DIST_GS	0x29	8.5.6.	Performs distance and grayscale acquisition	
GET_DIST_AMPLITUDE	0x22	8.5.7.	Performs distance and TOF amplitude acquisition	
GET_GS	0x24	8.5.8.	Performs grayscale acquisition	
GET_DCS	0x25	8.5.9.	Performs DCS acquisition	
GET_CALIBRATION_INFO	0x57	8.5.10.	Returns information about the calibration on the device	

Table 12: GET commands

8.3.3. Miscellaneous commands

Command	CMD	Ref.	Description	Comments
SET_OUTPUT	0x51	8.6.1.	Sets the outputs OUT1 or OUT2 external loads	
GET_INPUT	0x52	8.6.2.	Returns the status of the IN pin	
GET_TEMPERATURE	0x4A	8.6.3	Returns the chip temperature	

Command	CMD	Ref.	Description	Comments
GET_TOFCOS_VERSION	0x49	8.6.4.	Returns the TOFCOS version of the camera	
GET_CHIP_INFORMATION	0x48	8.6.5.	Returns the epc635 Chip ID and Wafer ID	
GET_PROD_DATE	0x50	8.6.6.	Returns the production date of the camera	
IDENTIFY	0x47	8.6.7.	Returns the device ID and the operating mode	
GET_ERROR	0x53	8.7.		

Table 13: Miscellaneous commands

8.3.4. Factory maintenance commands

These commands shall be used with highest care. Incorrect use may lead to camera malfunction or even may destroy the camera. It may be possible that the camera is not eye safe anymore !

Command	CMD	Ref.	Description	Comments
CALIBRATE_DRNU	0x41	8.8.1.	Performs the DRNU calibration	Factory command only
GET_CALIBRATION	0x43	8.8.2.	Returns the calibration data	
JUMP_TO_BOOTLOADER	0x44	8.8.3.	Branches to the boot-loader	
UPDATE_TOFCOS	0x45	8.8.4.	Copies the TOFCOS into the flash memory of the sensor	Boot loader command only
WRITE_CALIBRATION_DATA	0x4B	8.8.5.	Writes the calibration data into the flash memory	Deletes previous stored calibration
SET_MOD_FREQUENCY	0x05	8.8.6	Modulation frequency setting	
READ_REGISTER	0x4D		Reads a register of the epc635 chip	
WRITE_REGISTER	0x4C		Writes into a register of the epc635 chip	Incorrect use may lead to camera malfunction or may destroy the camera. It may be possible that the camera is not eye safe anymore !

Table 14: Factory maintenance commands

8.4. SET commands

8.4.1. SET_MOD_CHANNEL [0x0E]

In the case that more than one 3D TOF cameras (or in general high frequency modulated illumination sources, higher than several MHz) operate in the same scenery, 3D TOF cameras can get disturbed by interference effects. ESPROS 3D TOF cameras operate on the synchronous demodulation principle (super-heterodyne demodulation) which is like a narrow frequency bandpass filter given by the modulation frequency. Modulated light by a "disturber" needs to operate at the same or very similar frequency to disturb an ESPROS 3D TOF camera. However, if the "disturber" operates in this narrow frequency band, it may interfere other cameras.

Interference detection

The TOFcam-635-S has a built in interference detection which detects pixels with wrong distance data due to interference. The distance data of such interfered pixels are either marked with 'not valid' or return the last measurement value.

Interference avoidance

To prevent interference, the TOFcam-635-S camera has an option to slightly change the modulation frequency in order to "shift" away from a disturbers frequency. Therefore, the camera has predefined "modulation channels", each preset with a slightly shifted modulation frequency.

The camera can be set either to a fixed channel or an automatic frequency hopping mode. In the automatic frequency hopping mode, the camera "hops" to a different frequency if it detects interference.

Parameter	byte 0:	reserved	
		bit 2 … 7:	0
	byte 1:	Channel 0 … 15, **default**: Channel 0	
	others:	0x00	
Response type	0x00:	ACK	
Response time	t_{PROC} :	~ 25µs	

Example

Command e.g. | 0xF5 | **0x0E** | **0x01 0x01** 0x00 0x00 0x00 0x00 0x00 0x00 | 0xBD 0xAA 0x58 0xFC | (Frequency hopping ON, channel 1)

Channel	Center frequency 20MHz
0	20.00
1	19.20
2	19.30
3	19.40
4	19.50
5	19.60
6	19.70
7	19.80
8	19.90
9	20.10
10	20.20
11	20.30
12	20.40
13	20.50
14	20.60
15	20.70

Table 15: Modulation channels

8.4.2. SET_INT_TIME_DIST [0x00]

The integration time, called exposure time in 2D cameras, is the central parameter to control the camera. Like in any 2D camera, the exposure time is essential for good image quality. If the scenery is in the dark, a longer exposure time is necessary in order to make dark areas in the picture visible. On the other hand, a high brightness in the scenery needs a shorter exposure time in order not to saturate the pixels. Typically, the exposure time setting in modern digital cameras is set automatically, dependent on the illumination situation.

Every 3D camera depends also on a good integration time setting. The longer the integration time, the higher the sensitivity. Thus, a longer integration time allows the detection of objects farther away. However, high reflective objects in close distance lead to saturation in one or more pixels so distance measurement is no longer possible.

The TOFcam-635-S allows manual and automatic integration time operation. In the manual mode, the integration time can be set by a parameter previous to the exposure.

In the automatic mode, the integration time is set automatically based on the brightness of the scenery.

⚠ It is to note that a longer integration time leads to the collection of more ambient-light. The more ambient-light collected, the higher the distance noise due to the shot noise created by the ambient-light. Thus, the shorter the integration time, the lower the distance noise. As a rule of thumb, an integration time less than 1'000µs allows a very efficient ambient-light suppression. Integration times greater than 1'000µs should be used only in indoor applications.

It is also to note that the reflectivity of an object can have an impact on the distance measurement accuracy.

IntTimeIn	No HDR	HDR	Default [µs]
0x00	Integration time used for the full pixel-field or the ROI	1. integration time	125
0x01		2. integration time	0
0x02		3. integration time	0
0x03		4. integration time	0
0x04			
0x05			
0xFF			N/

Table 16: Integration time index, refer also to Chapter 8.4.4.

Parameter byte 0: IntTimeIndex. Refer to Table 16.
byte 1, 2: Integration time in microseconds, 16 bit unsigned integer, Range: 1 … 1'000 µs.
others: 0x00

Response type 0x00: ACK

Response time t_{PROC} : ~ 25µs

Example

Command e.g. | 0xF5 | **0x00** | **0x00 0x1E 0x00** 0x00 0x00 0x00 0x00 0x00 | 0x47 0x7 0xEC 0xC0 | (integration time 0 = 30µs)

Consider the following amplitude returns for adequate integration time settings:

TOF amplitude	Consideration
<100 LSB	Distance results contain significant distance noise. Increase the integration time and/or apply the temporal filter to reduce the distance noise. Refer to Chapter 8.4.6. and 8.5.3
100 ... 1'900 LSB	Good measurement data with low distance noise. However, temporal filtering is recommended. Refer to Chapter 8.4.6. and 8.5.3
500 ... 1'900 LSB	Ideal amplitude for best performing distance data.
>1'900 LSB	Distance result can be wrong due to saturation.

Table 17: TOF amplitude rating

8.4.3. SET_INT_TIME_GS [0x01]

Sets the integration time for grayscale measurements.

Parameter byte 0, 1: Integration time in microseconds, 16 bit unsigned integer, Range: 1 … 50'000 µs.
Automatic Mode: Integration time = 0, used for ambient light compensation, **default**.
others: 0x00

Response type 0x00: ACK

Response time t_{PROC} : ~ 25µs

Example

Command e.g. | 0xF5 | **0x01** | 0x00 **0x1E 0x00** 0x00 0x00 0x00 0x00 0x00 | 0x59 0xB0 0xAC 0x6B | (integration time GS = 30µs)

8.4.4. SET_HDR [0x0D]

Sets the type of the high-dynamic range (HDR) for distance acquisition. They are preferably used in distance and TOF amplitude mode. They do not affect the grayscale modes. Please refer also to Chapter 8.5.7. Two different modes are available:

1. Spatial HDR

In this mode, different integration times set with IntTimeIndex0/1/2/3 are used simultaneously during the acquisition of an image. IntTimeIndex0/2/4 are used for the even rows and IntTimeIndex1/3/5 for the odd rows. After image acquisition, the TOFCOS then selects the pixel with the “best” amplitude value of the up to four pixels values from the two vertical adjacent pixels and stuffs (patches) the other pixel of this pixel pair with the same value. The result is an image with a very high dynamic range, best possible frame rate but with a lower vertical resolution. Virtually, the pixel becomes a vertical rectangle because always the two vertical neighbor pixels contain the same value. Refer also to Table 16.

It is possible to use one pair, 2 integration times, only. Therefore, set the not used integration time pair to zero. In this case, the camera acquires one image by applying two different integration times for the even and the odd rows. Thus, the image acquisition is faster because there is one acquisition only instead of two.

2. Temporal HDR

The camera acquires and transmits image data in a consecutive and incrementing sequence by using IntTimeIndex0, IntTimeIndex1, IntTimeIndex2, IntTimeIndex3, IntTimeIndex4 and IntTimeIndex5. The host software has then to patch the up to four images to one HDR image by a selection of the best amplitude for each pixel. It is possible to use 2 or 3 integration times only. In this case, set not used integration times to zero.

Parameter	byte 0:	0 = HDR off, **default**	
		1 = spatial HDR	1st step: 2 integration times in 1 frame using row reduction - and additionally 2nd step: Time-wise by 2 consecutive frames.
		2 = temporal HDR	Time-wise by 2, 3 or 4 consecutive frames, only non-zero values for IntTimeIndex are acquired.
	others:	0	
Response type	0x00:	ACK	
Response time	t_{PROC} :	~ 25µs	

Example

Command e.g. | 0xF5 | **0x0D** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x2A 0x7C 0x6A 0xBD | (HDR off)

8.4.5. SET_ROI [0x02]

A full image of the TOFcam-635-S has a pixel-field of 160x 60 pixels. A “region of interest” acquires only a selected number of pixels which are necessary for the application. This reduces the amount of readout data and increases the frame rate.

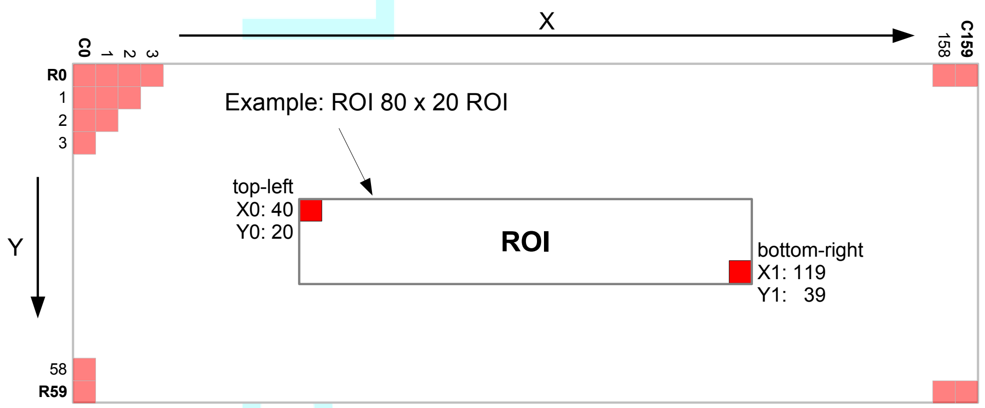


Figure 32: ROI setting

Parameter	byte 0, 1: Coordinate X0, 16 bit unsigned integer	
	byte 2, 3: Coordinate Y0, 16 bit unsigned integer	
	byte 4, 5: Coordinate X1, 16 bit unsigned integer	
	byte 6, 7: Coordinate Y1, 16 bit unsigned integer	
	Ranges:	X0, X1 = 0 … 159, Y0, Y1 = 0 … 59, **Default**: Full image 160x60 pixel
	Boundaries:	X1 – X0 > 7 pixel, Y1 – Y0 > 3 pixel, each increments by multiple of 4 pixels.
Response type	0x00: ACK	
Response time	t_{PROC} : ~ 25µs	

Example

Command e.g. | 0xF5 | **0x02** | **0x00 0x00 0x00 0x00 0x9F 0x00 0x3B 0x00** | 0xB9 0xFC 0xA9 0x69 | (X0 = 0, Y0 = 0, X1 = 159, Y1 = 59)

8.4.6. SET_TEMPORAL_FILTER_WFOV [0x07]

The temporal filter is a Kalman filter, which uses two parameters: A threshold 'T' and a filter value 'k'. As long as new distance measurement values are in between ±'T' to the former distance measurement, the filter takes the average of previous distance measurement values, depending on the 'k' value. The temporal filter applies to all pixels individually.

Parameter	byte 0, 1:	Filter threshold in mm, typ. value is 300 mm
	byte 2, 3:	Filter factor in steps of units. The lower the number, the stronger the filter effect, however, the slower the response to distance changes. Ideal values are between 10 and 200. If the factor is set to 1'000, the filter is disabled (**default**).
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example
Command e.g. | 0xF5 | **0x07** | **0x2C 0x01 0x64 0x00** 0x00 0x00 0x00 0x00 | 0xE9 0x45 0xAD 0xEE | (Threshold = 300 mm, factor = 100)

8.4.7. SET_AVERAGE_FILTER [0x0A]

This spatial filter uses a 2x2 pixel sliding window. It averages the distance values of the four pixels and places the result to the upper left pixel in the 2x2 window (refer to Figure 33). The sliding window is shifted all across the image. The last row and column of the image remain as they are.

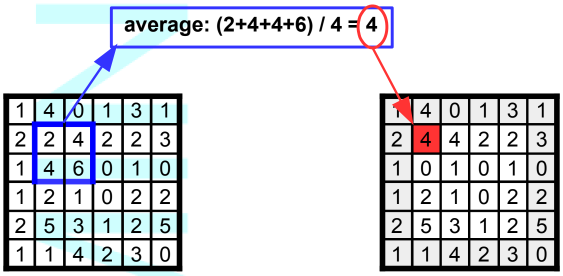


Figure 33: Example of a 2 x 2 pixel sliding window for the median filter, sliding means, do the same for all columns and rows of the image

Parameter	byte 0:	0 = disabled (**default**), 1 = enabled
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example
Command e.g. | 0xF5 | **0x0A** | **0x01** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x1E 0x19 0x54 0x95 | (Average filter enabled)

8.4.8. SET_MEDIAN_FILTER [0x0B]

This spatial filter uses a 3x3 pixel sliding window. It selects the median value of the 9 pixel in the window and places the result to the center pixel in the 3x3 window (refer to Figure 34). The sliding window is shifted all across the image. First and last row as well first and last column of the image remain as they are.

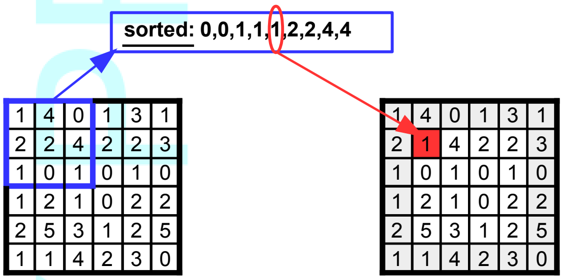


Figure 34: Example of a 3 x 3 pixel sliding window for the median filter, sliding means, do the same for all columns and rows of the image

Parameter	byte 0:	0 = disabled (**default**), 1 = enabled
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example
Command e.g. | 0xF5 | **0x0B** | **0x01** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x00 0xAE 0x14 0x3E | (median filter enabled)

8.4.9. SET_INTERFERENCE_DETECTION [0x11]

Set interference detection settings.

Parameter	byte 0:	0 = disabled, 1 = enabled (**default**)
	byte 1:	0 = mark pixel with status code, 1 = use last valid value (**default**)
	byte 2/3:	interference detection limit (**default 500**)
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x11** | **0x01 0x01 0x90 0x01** 0x00 0x00 0x00 0x00 | 0x93 0xD8 0x1B 0x77 | (enabled, use last value, 400lsb)

8.4.10. SET_EDGE_DETECTION [0x10]

Set edge detection settings.

Parameter	byte 0,1:	0 = disabled, else edge detection threshold (**default 300**)
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x10** | **0x2C 0x01** 0x00 0x00 0x00 0x00 0x00 0x00 | 0xDA 0x6E 0xA8 0x50 | (threshold 300)

8.4.11. SET_FRAME_RATE [0x0C]

This command can be used to limit the maximal frame rate. The frame rate basically depends on the integration time plus the processing time. There are two different cases to consider:

1. If the integration time plus the processing time is less than the set frame time, the set frame time limits the effective frame rate.
2. If the integration time plus the processing time is greater than set frame time, the set frame rate setting is inactive. In this case, the frame rate is given by the integration rate plus the processing time.

Parameter	byte 0, 1:	frame time (= 1 / frame rate) in milliseconds, 16 bit unsigned integer. Range: 10 – 200ms. **Default** = 1 (allows max. possible frame rate)
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x0C** | **0x14 0x00** 0x00 0x00 0x00 0x00 0x00 0x00 | 0x2A 0xF7 0xB1 0x81 | (50 fps)

8.4.12. SET_AMPLITUDE_LIMIT [0x09]

Sets the amplitude limits for the confidence information. The limits decide if distance is valid and confidence bits are set. Refer to Table 19.

Parameter	byte 0:	0 … 3 = Index of the amplitude limit to be set, for wide field , 4 = Index for narrow field
	byte 2, 3:	Amplitude limit in LSB, 16 bit unsigned integer. Ranges and **defaults** refer to Table 19.
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x09** | **0x00 0x64 0x00** 0x00 0x00 0x00 0x00 0x00 | 0xE7 0x34 0xAE 0x47 | (Set limit 0 = 100 LSB)

8.4.13. STOP_STREAM [0x28]

Stops the stream if the camera is in streaming mode. Refer to Figure 29 and Chapters 8.5.5 - 8.5.9.

Parameter	no, all bytes 0x00. **Default**: Camera is not streaming.	
Response type	0x00:	ACK
Response time	t_{PROC} :	Max. calculation time of 1 image. Depends on settings.

Example

Command e.g. | 0xF5 | **0x28** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xF9 0x7F 0x68 0x81|

8.4.14. SET_COMPENSATION [0x55]

Without calibration and runtime compensation, the distance measurement is rather inaccurate and it drifts by changes in temperature and ambient-light. Thus, the TOFcam-635-S is factory calibrated and it uses a runtime compensation for best possible accuracy. However, it is possible but not recommended to turn the runtime calibration off.

Parameter	byte 0:	Distance response non-uniformity compensation (DRNU), 0 = off, 1 = active (**default**)
	byte 1:	Ambient-light compensation, 0 = off, 1 = active (**default**)
	byte 2:	Temperature compensation, 0 = off, 1 = active (**default**)
	others:	0
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x55** | **0x01 0x01 0x01** 0x00 0x00 0x00 0x00 0x00 | 0x7F 0x70 0x24 0x71 | (enable all compensations)

8.4.15. SET_DLL_STEP [0x06]

The DLL is a delay line which is placed into the illumination modulation signal chain. Adding a delay is like moving the distance of an object to a farther distance. Based on the speed of light, a delay of one nanosecond (ns) represents a distance change of 150mm.

Sets the number of DLL steps for artificial phase/distance shifting. One step is approx. 2.15ns which is a distance change of approx. 315mm.

Parameter	byte 0:	Number of DLL steps. **Default** = 0
	others:	0x00
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25 µs

Example

Command e.g. | 0xF5 | **0x06** | **0x01** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x93 0x2D 0x14 0x7C | (Number of steps = 1)

8.5. GET commands

The GET commands do the image acquisition and the data readout.

8.5.1. Acquisition modes

The acquisition modes in the “GET” commands in Chapters 8.5.5 to 8.5.9 have the following meaning:

Acquisition mode	Parameter byte 0	Description
Single measurement	0x00	The camera acquires one image
Pipelined single measurement	0x01	Parallel to the data transmission of an image on command, the next image is already acquired. This reduces the processing time of the next command. This mode gets almost the same frame rate as the streaming mode.
Streaming mode	0x02	The camera acquires continuously images and streams the data. The stream can be terminated either by an other acquisition or the STOP_STREAM command

Table 18: Acquisition mode definition

8.5.2. Acquisition data output formats

The data output formats of the GET commands are listed in Table 19 and 20 and are according to the selected operation modes:

Confidence bit 15, 14	Distance bit 13 … 0	Amplitude limits	Definitions and comments
Definition	0 … 7'500d or status	---	Mod. frequency 20 MHz FOV: Full frame 160x60 pixel or ROI. Refer to Figure 2 Distance range: 0 … 7.5 m Resolution: 1 mm/LSB Data: 16 bit: 2 bit confidence and 14 bit unsigned integer distance
00	< 7'500d	TOF amplitude > **AmpLimit0** **Default** = 50 LSB	**Very low amplitude:** The result shows the presence of an object, but distance information is very inaccurate.
10	< 7'500d	TOF amplitude > **AmpLimit1** **Default** = 100 LSB	**Weak amplitude:** Distance result is usable but has reduced accuracy.
10	< 7'500d	TOF amplitude > **AmpLimit2** **Default** = 200 LSB	**Good amplitude:** Good distance information.
11	< 7'500d	TOF amplitude > **AmpLimit3** **Default** = 500 LSB	**Excellent amplitude:** Most accurate distance measurement.
Don't care	> 7'500d	TOF amplitude < **AmpLimit0**	**Distance not available or out of range:** Check distance status.
Status	16'001d	---	Low TOF amplitude
	16'002d	---	Exceeds ADC conversion limits
	16'003d	---	Pixel saturation
	16'007d	---	Modulation interference or Motion-blur
	16'008 d	---	Filtered out by edge detection

Table 19: Definition and decision table for distance data and confidence (refer also to Chapter 8.4.12.)

In the cases where the camera uses modes responding with distance results only and without other quality information, the distance data format per pixel encloses two bits with quality information of the measurement, called confidence data. Refer to Table 19. This confidence data is based on the TOF amplitude. Refer also to Chapters 8.5.5 and 8.5.6.

The levels for checking the confidence are initialized by default, to values out of practice. A change to application specific values is possible. Refer to Chapter 8.4.12.

It is to note that the reflectivity of the object can have an impact on the distance measurement accuracy. Make sure, the amplitudes are in the specified range.

Definition	Type	Data	Amplitude
TOF amplitude	AMP	6 bit: 4 bit not used and 12 bit unsigned integer TOF amplitude.	0 … 2'896 LSB, no status
Grayscale	GS	8 bit unsigned integer grayscale	0 … 255 LSB, no status
DCS data	DCSx	16 bit: 12 bit unsigned integer DCS, 3 bit not used, 1 bit saturation flag Signed DCS value = readout value – 2'048 LSB.	0 … 4'095 LSB, no status

Table 20: Definitions of other data formats

8.5.3. Response header

Every response to a command request for distance, grayscale, amplitude and DCSx includes this header as a fix part of the transmission. It contains information about the parameter settings for the acquisition and to the system. The application can skip the information if not needed.

Entry	Format	Bytes	Index	Comment
Header version	8 bit unsigned integer	1	0	Protocol identification against future, changed versions.
Frame counter	16 bit unsigned integer	2	1	Increment per frame, roll over at 65'535
Timestamp	16 bit unsigned integer	2	3	Increment per millisecond, roll over at 65'535s
TOFCOS version	MSBytes: 16 bit unsigned Version LSBytes: 16 bit unsigned Sub-version	4	5	Refer to Chapter 8.6.4
Hardware version	8 bit unsigned integer	1	9	Refer to Chapter 8.6.7
Chip ID	16 bit unsigned integer	2	10	Refer to Chapter 8.6.5
Image width (x-axis)	16 bit unsigned integer	2	12	Refer to Chapter 8.4.5
Image height (y-axis)	16 bit unsigned integer	2	14	
Image origin X	16 bit unsigned integer	2	16	
Image origin Y	16 bit unsigned integer	2	18	

Table 21: Header parameters

Entry	Format	Bytes	Index	Comment
CurrentIntegrationTime3D	16 bit unsigned integer	2	20	Used integration time. Spatial HDR mode: It is the first of the two integration times.
CurrentIntegrationTimeGrayscale	16 bit unsigned integer	2	24	Used integration time.
IntegrationTimeGrayscale	16 bit unsigned integer	2	26	Refer to Chapter 8.4.3
IntegrationTime0	16 bit unsigned integer	2	28	Refer to Chapter 8.4.2
IntegrationTime1	16 bit unsigned integer	2	30	
IntegrationTime2	16 bit unsigned integer	2	32	
IntegrationTime3	16 bit unsigned integer	2	34	
InterferenceDetectionLevel	16 bit unsigned integer	2	40	
EdgeDetectionThreshold	16 bit unsigned integer	2	42	
AmplitudeLimit0	16 bit unsigned integer	2	44	Refer to Chapter 8.4.12
AmplitudeLimit1	16 bit unsigned integer	2	46	
AmplitudeLimit2	16 bit unsigned integer	2	48	
AmplitudeLimit3	16 bit unsigned integer	2	50	
DistanceTemporalFilter-Factor	16 bit unsigned integer	2	57	Temporal Filter all pixels. Refer to Chapter 8.4.6
DistanceTemporalFilter-Threshold	16 bit unsigned integer	2	59	
Modulation frequency	8 bit unsigned integer 0: 10MHz, 1: 20MHz	1	65	Refer to Chapter 8.8.6
Modulation channel	8 bit unsigned integer	1	66	Modulation channel selection to prevent from multi camera inter-ference. Refer to Chapter 8.4.1.
Flags	**Bit / Abbr. / Comment** 0 / AM / AutoModulationChannel 1 / AI / AutoIntegrationTime 2 / AF / Average filter 3 / MF / Median filter 4 / CD / Compensated DRNU 5 / CT / Compensated temperature 6 / CA / Compensated ambient-light 7 / SH / Spatial HDR	2	67	

<table>
<tr><th>Entry</th><th>Format</th><th>Bytes</th><th>Index</th><th>Comment</th></tr>
<tr><td></td><td><table>
<tr><td>8</td><td>TH</td><td>Temporal HDR</td></tr>
<tr><td>9</td><td>TP</td><td>Input pin</td></tr>
<tr><td>10</td><td>UL</td><td>Use last value (interference)</td></tr>
<tr><td>11</td><td>RI</td><td>Reduced illumination power</td></tr>
<tr><td>12..15</td><td>NU</td><td>not used</td></tr>
</table></td><td></td><td></td><td></td></tr>
</table>

Table 21 cont.: Header parameters

8.5.4. Warm-up

The distance accuracy of TOF cameras is sensitive to temperature change due to the temperature dependent electron mobility velocity in semiconductors. This phenomenon effects the speed of the electrons of the illumination, the illumination driver, the pixel of the imager chip, etc. Thus, an effective temperature compensation is implemented into the TOFcam-635. However, if there are fast and large temperature changes of the camera, the measured distance may deviate significantly from the real object distance. Such a large and fast temperature step takes place when the camera is powered on, until the operating temperature reaches its equilibrium. Figure 35 shows a typical error curve of a pixel during power up.

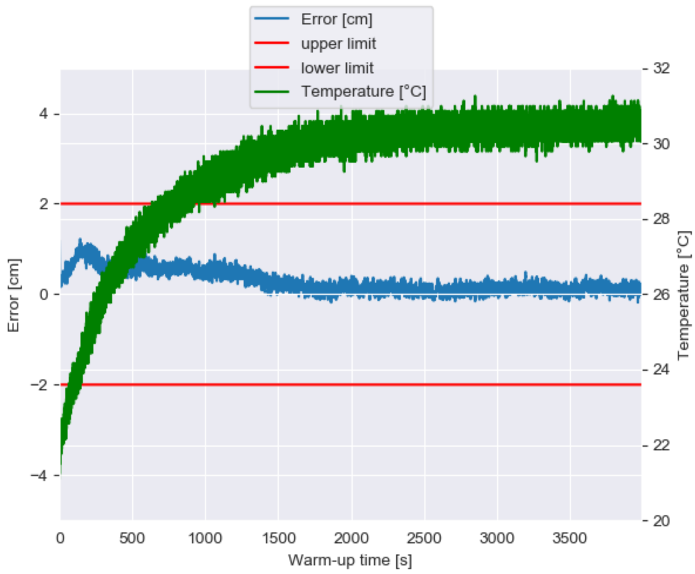


Figure 35: Typical warm-up phase of camera at room temperature

8.5.5. GET_DIST [0x20]

Performs distance acquisition. Refer to Figure 36. It returns, in streaming mode continuously, the result or status. For parameter settings and response details, refer to 18 and 19.

Parameter byte 0: Acquisition mode. Refer to Table 18.
others: 0
Response type 0x03: Distance
Response data 80 bytes header (refer to Chapter 8.5.3) + max. 160x60 pixel x 2 bytes/pixel distance data (refer to Table 19).
Response time up to ~100ms depending on settings

Example
Command e.g | 0xF5 | **0x20** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x62 0xAC 0xA8 0xCC | (Acquisition mode 0)
Response e.g | 0xFA | **0x03** | **0x50 0x4B** | **0x28 0x0F 0x00 0x00 … (19'280 bytes total)** | CRC (4 bytes) |

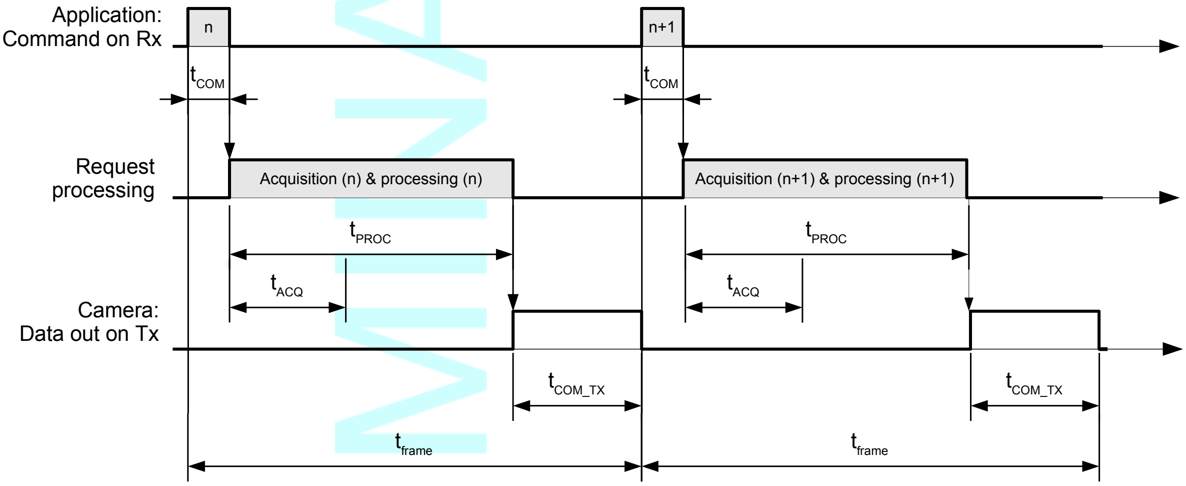


Figure 36: Timing of a single distance measurement

8.5.6. GET_DIST_GS [0x29]

Performs distance and grayscale acquisition. It returns, in streaming mode continuously, the result or status. For parameter settings and response details, refer to Table 18, 18 and 20.

Parameter byte 0: Acquisition mode. Refer to Table 18.
others: 0
Response type 0x0A: Distance and grayscale
Response data 80 bytes header (refer to Chapter 8.5.3) + max. 160x60 pixel x 3 bytes/pixel
with 16 bit distance data (refer to Table 19) and 8 bit grayscale data (refer to Table 20).
Response time up to ~150ms depending on settings

Example
Command e.g | 0xF5 | **0x29** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xE7 0xC8 0x28 0x2A | (Acquisition mode 0)
Response e.g | 0xFA | **0x0A** | **0xD0 0x70** | **0x28 0x0F 0x00 0x00 … (28'880 bytes total)** | CRC (4 bytes) |

8.5.7. GET_DIST_AMPLITUDE [0x22]

Performs distance and TOF amplitude acquisition. It returns, in streaming mode continuously, the result or status. For parameter settings and response details, refer to Table 18, 19 and 20.

Parameter byte 0: Acquisition mode. Refer to Table 18.
others: 0
Response type 0x05: Distance and amplitude
Response data 80 bytes header (refer to Chapter 8.5.3) + max. 160x60 pixel x 4 bytes/pixel
16 bit distance data (refer to Table 19) and 16 bit TOF amplitude (refer to Table 20).
Response time up to ~150ms depending on settings

Example
Command e.g. | 0xF5 | **0x22** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xE9 0xDF 0xE8 0x9E | (Acquisition mode 0)
Response | 0xFA | **0x05** | **0x50 0x96** | **0x28 0x0F 0x00 0x00 … (38'480 bytes total)** | CRC (4 bytes) |

8.5.8. GET_GS [0x24]

Performs grayscale acquisition. It returns, in streaming mode continuously, the result or status. For parameter settings and response details, refer to 18 and 20.

Parameter	byte 0:	Acquisition mode. Refer to Table 18.
	others:	0
Response type	0x06:	Grayscale
Response data	80 bytes header (refer to Chapter 8.5.3) + max. 160x60 pixel x 1 byte/pixel with 8 bit grayscale data (refer to Table 20).	
Response time	up to ~100ms depending on settings	

Example
Command e.g | 0xF5 | **0x24** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x74 0x4B 0x28 0x68 | (Acquisition mode 0)
Response | 0xFA | **0x06** | **0xD0 0x25** | **0x28 0x0F 0x00 0x00 … (9'680 bytes total)** | CRC (4 bytes) |

8.5.9. GET_DCS [0x25]

Performs DCS acquisition. It returns, in streaming mode continuously, the result or status. For parameter settings and response details, refer to 18 and 20.

Parameter	byte 0:	Acquisition mode. Refer to Table 18.
	others:	0
Response type	0x07:	DCS data
Response data	1 command "GET_DCS" transmits the data in one or two packets with the following data, 80 bytes header (refer to Chapter 8.5.3) + 1 byte packet number + 4 bytes total size + max. 50'000 bytes (160x60 pixel x 2 bytes/pixel with 16 bit DCS data (refer to Table 20)). Only applicable to mode 0, refer to Fehler: Referenz nicht gefunden.	
Response time	up to ~200ms depending on settings	

Example
Command e.g | 0xF5 | **0x25** | **0x00** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x6A 0xFC 0x68 0xC3 | (Acquisition mode 0)
Response | 0xFA | **0x07** | **0x50 0xC3** | **0x00** | 0x00 0x2C 0x01 0x00 | **0x28 0x0F 0x00 … (50'000 bytes total)** | CRC (4 bytes) |
| 0xFA | **0x07** | **0xB0 0x68** | **0x01** | 0x00 0x2C 0x01 0x00 | **0x28 0x0F 0x00 … (26'800 bytes total)** | CRC (4 bytes) |

8.5.10. GET_CALIBRATION_INFO [0x57]

Returns information about the calibration on the device. These includes a flag about calibration data consistency.

Parameter	all 0	
Response type	0xF6:	Calibration info data
Response data	1 byte modulation frequency (0 = 10MHz, 1 = 20MHz),	
	1 byte binning (0 = no binning, 1 = horizontal/vertical binning),	
	9 bytes unused	
	1 byte CRC correct flag (0 = incorrect, 1 = correct),	
	2 bytes unused	
Response time	~10ms	

Example
Command e.g | 0xF5 | **0x57** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xBA 0xDC 0xEF 0x5E |
Response e.g | 0xFA | **0xF6** | **0x0D 0x00** | **0x01 0x00 | 0x00 0x00 0x00 0x00 0x00 0x00 0x0 0x00 0x00 0x00 | 0x01** | 0x01 0x60 0x87 0xD8 (20MHz, no binning, CRC correct)

8.6. Miscellaneous commands

8.6.1. SET_OUTPUT [0x51]

Sets the outputs OUT1 or OUT2. Can be used by the application to switch external loads.

Parameter	byte 0:	Open-drain OUT1, 0x00 = OFF (**default**), 0x01 = ON
	byte 1:	Open-drain OUT2, 0x00 = OFF (**default**), 0x01 = ON
	others:	0x00
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x51** | **0x01 0x01** 0x00 0x00 0x00 0x00 0x00 0x00 | 0x25 0x5A 0x1D 0x10 | (Set both outputs = ON)

8.6.2. GET_INPUT [0x52]

Returns the status of the IN pin. Can be used by the application to read an external digital signal, e.g. a switch status.

Parameter	no, all bytes 0x00	
Response type	0x0B:	IO
Response data	1 byte:	0x00 = input LOW, 0x01 = input HIGH
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x52** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xB2 0x8C 0x2F 0x51 |

Response e.g. | 0xFA | **0x0B** | **0x01 0x00** | **0x00** | 0xCD 0x50 0x9D 0xE0 | (Input = LOW)

8.6.3. GET_TEMPERATURE [0x4A]

Returns the chip temperature during last distance acquisition.

Parameter	no, all bytes 0x00	
Response type	0xFC:	Data
Response data	2 bytes:	Temperature, 0.01 ºC / LSB, 16 bit 2's complement signed integer.
Response time	t_{PROC}:	~ 25 µs

Example

Command e.g. | 0xF5 | **0x4A** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x1F 0xF8 0x6E 0x87 |

Response e.g. | 0xFA | **0xFC** | **0x02 0x00** | **0x47 0x13** | 0x54 0x1E 0x4C 0x14 | (Temperature = 49.35°C)

8.6.4. GET_TOFCOS_VERSION [0x49]

Returns the TOFCOS version and sub-version of the camera.

Parameter	no, all bytes 0x00	
Response type	0xFE:	Data
Response data	4 bytes:	byte 0, 1: Subversion, 16 bit unsigned integer
		byte 2, 3: Version, 16 bit unsigned integer
Response time	t_{PROC}:	~ 25 µs

Example

Command e.g. | 0xF5 | **0x49** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x8A 0x3C 0x6E 0x7E |

Response e.g. | 0xFA | **0xFE** | **0x04 0x00** | **0x0E 0x00 0x01 0x00** | 0xE6 0xC5 0x85 0xA0 | (Version 1.14)

8.6.5. GET_CHIP_INFORMATION [0x48]

Returns the Chip ID and Wafer ID of the used epc635 imager chip.

Parameter	no, all bytes 0x00	
Response type	0xFD:	Data
Response data	4 bytes:	byte 0, 1: Chip ID, 16 bit unsigned integer
		byte 2, 3: Wafer ID, 16 bit unsigned integer
Response time	t_{PROC}:	~ 25 µs

Example

Command e.g. | 0xF5 | **0x48** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x94 0x8B 0x2E 0xD5|

Response e.g. | 0xFA | **0xFD** | **0x04 0x00** | **0x10 0x04 0x10 0x00** | 0x49 0x2C 0xBB 0x6A | (Chip ID 1040 , Wafer ID 16)

8.6.6. GET_PROD_DATE [0x50]

Returns the production date of the camera.

Parameter no, all bytes 0x00

Response type 0xF9: Data
Response data 2 bytes: byte 0: Last two digits of the year as unsigned integer e.g. 18
byte 1: Number of the week as integer e.g. 22

Response time ~ 25 µs

Example
Command e.g. | 0xF5 | **0x50** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x39 0xFF 0x6F 0x3 |
Response e.g. | 0xFA | **0xF9** | **0x02 0x00** | **0x12 0x16** | 0x4A 0x68 0xF7 0xA7 | (year 18, week 22)

8.6.7. IDENTIFY [0x47]

Returns the device identification ID and the mode (normal operation or boot-loader mode if a TOFCOS update was not successful). Is the camera in boot-loader mode, run a TOFCOS update with the GUI ESPROS_TOFCAM635 or with the boot-loader (see next). The GUI detects a missing TOFCOS and runs an update automatically. This command may be used also for communication check.

Parameter no, all bytes 0x00

Response type 0x02: Data

Response data 4 bytes: byte 0: Hardware version
byte 1: Device type is TOFcam-635 = 0x00
byte 2: Chip type is epc635 = 0x04
byte 3: 0x00 = normal operation, 0x80 = boot-loader

Response time t_{PROC} : ~ 25µs

Example
Command e.g. | 0xF5 | **0x47** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x8C 0x7B 0x6E 0xC5 |
Response e.g. | 0xFA | **0x02** | **0x04 0x00** | **0x00 0x00 0x04 0x00** | 0xE5 0x48 0x22 0x5D | (HW version 0, normal operation)

8.7. GET_ERROR [0x53]

Returns a number of the error of the device.

Parameter no, all bytes 0x00

Response type 0xFF: Data

Response data 2 bytes: Error number
Error number 0: Nor error
Error number 1: Timeout
Error number 2: Error data acquisition
Error number 3: Error sensor communication

Response time t_{PROC}: ~ 25 µs

Example
Command e.g. | 0xF5 | **0x53** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0xAC 0x3B 0x6F 0xFA |
Response e.g. | 0xFA | **0xFF** | **0x02 0x00** | **0x03 0x00** | 0xC7 0x30 0x55 0x4B | (Error sensor communication)

8.8. Factory maintenance commands

⚠ Use these commands only if you are familiar with its operation. Wrong usage may lead to an uncalibrated, non-working or even damaged TOFcam-635! In general, these commands are not needed for standard usage of the TOFcam-635.

8.8.1. CALIBRATE_DRNU [0x41]

Performs the DRNU calibration in the calibration box (more information about this from your ESPROS sales representative). It is to note that this command can take several minutes. Never remove the camera from the calibration box until the calibration process has been finished.

⚠ Deletes previous stored calibration!

Parameter	byte 0:	0 = calibrate and verify, 1 = verify only
	byte 1:	bit0 = flag for wide field, bit1 = unused
	byte 2:	0x45
	byte 3:	0x67
	byte 4:	0x89
	byte 5:	0xAB
	byte 6:	0xCD
	byte 7:	0xEF
Response type	0x00:	ACK
Response time	t_{PROC} :	~ 15minutes

Example

Command e.g. | 0xF5 | **0x41** | **0x01 0x01 0x45 0x67 0x89 0xAB 0xCD 0xEF** | 0x20 0x11 0x7 0x3E |

8.8.2. GET_CALIBRATION [0x43]

Returns the calibration data after t_{PROC} . Use this command to backup the calibration data before a TOFCOS update or new calibration.

Parameter	no, all bytes 0x00	
Response type	0xFA:	Calibration data, 128kBytes data directly read from the flash, transmitted in 3 packets (2 packets with 50'000 bytes and the last with 31072 bytes). Each packet starts with 1 byte packet number + 4 bytes total size
Response data	0 byte	
Response time	t_{PROC} :	~ 25µs

Example

Command e.g. | 0xF5 | **0x43** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x9A 0x9C 0xEE 0x61

Response e.g | 0xFA | **0xFA** | **0x50 0xC3** | **0x00** | **0x00 0x00 0x02 0x00** | **0x28 0x0F 0x00 … (50'000 bytes total)** | CRC (4 bytes) |
| 0xFA | **0xFA** | **0x50 0xC3** | **0x01** | **0x00 0x00 0x02 0x00** | **0x28 0x0F 0x00 … (50'000 bytes total)** | CRC (4 bytes) |
| 0xFA | **0xFA** | **0x60 0x79** | **0x02** | **0x00 0x00 0x02 0x00** | **0x28 0x0F 0x00 … (26'800 bytes total)** | CRC (4 bytes) |

8.8.3. JUMP_TO_BOOTLOADER [0x44]

Stops all normal operation activities and branches to the boot-loader. The boot-loader answers to this and all following commands. Refer also to Chapter 8.9.

Parameter	no, all bytes 0x00	
Response type	0x00:	ACK
Response time	t_{PROC} :	< 10ms

Example

Command e.g. | 0xF5 | **0x44** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x19 0xBF 0x6E 0x3C |

8.8.4. UPDATE_TOFCOS [0x45]

Boot-loader command only: Copies the TOFCOS into the flash memory of the sensor. It returns acknowledge after t_{PROC}.

Procedure 1st, write control byte "start" with password and file size; 2nd, write control byte "write" with index and data; 3rd, write control byte "complete".

Parameter 8 bytes: Contents differs and depends on operation step: Refer to Table 22.

Step	Action	Byte 7	Byte 6	Byte 5	Byte 4	Byte 3	Byte 2	Byte 1	Byte 0
1st	Start	Size of the update file				Password = 0x654321			**0x00**
2nd	Write data	TOFCOS data (4 bytes)				TOFCOSData[index] (3 bytes)			**0x01**
3rd	Complete	All 7 bytes = 0x00							**0x02**

Table 22: Boot-loader data format

Response type 0x00: ACK
Response time t_{PROC} : <400ms

Example
Command e.g.
| 0xF5 | **0x45** | **0x00 0x21 0x43 0x65 0x10 0x00 0x00 0x00** | 0xBF 0x90 0xC2 0x9F | (Start for 16 byte file size)
| 0xF5 | **0x45** | **0x01 0x00 0x00 0x00 0x10 0x4A 0x56 0x50** | 0x1C 0x41 0xAC 0x14 | (Write data to index 0)
| 0xF5 | **0x45** | **0x02 0x00 0x00 0x00 0x00 0x00 0x00 0x00** | 0x69 0x85 0x52 0x7C | (Complete)

8.8.5. WRITE_CALIBRATION_DATA [0x4B]

Writes the calibration data into the flash memory. This data is used during runtime DRNU compensation.

Deletes previous stored calibration!

Procedure 1st, write control byte "start" with password and file size; 2nd, write control byte "write" with index and data; 3rd, write control byte "complete".

Parameter 8 bytes: Contents differs and depends on operation step: Refer to Table 23.

Step	Action	Byte 7	Byte 6	Byte 5	Byte 4	Byte 3	Byte 2	Byte 1	Byte 0
1st	Start	Size of the update file				Password = 0x654321			**0x00**
2nd	Write data	Calibration data (4 bytes)				CalibrationData[index] (3 bytes)			**0x01**
3rd	Complete	All 7 bytes = 0x00							**0x02**

Table 23: Boot-loader data format

Response type 0x00: ACK
Response time t_{PROC} : <400ms

Example
Command e.g.
| 0xF5 | **0x4B** | **0x00 0x21 0x43 0x65 0x10 0x00 0x00 0x00** | 0xB9 0xD7 0xC2 0x24 | (Start for 16 byte file size)
| 0xF5 | **0x4B** | **0x01 0x00 0x00 0x00 0x10 0x4A 0x56 0x50** | 0x1A 0x06 0xAC 0xAF | (Write data to index 0)
| 0xF5 | **0x4B** | **0x02 0x00 0x00 0x00 0x00 0x00 0x00 0x00** | 0x6F 0xC2 0x52 0xC7 | (Complete)

8.8.6. SET_MOD_FREQUENCY [0x05]

Sets the modulation frequency. The modulation frequency defines the operating range, the distance resolution and distance noise.

Parameter byte 0: 0x00 = 10 MHz; 0x01 = 20 MHz (Default)
others: 0x00
Response type 0x00: ACK
Response time t_{PROC} : ~ 25µs

Example
Command e.g. | 0xF5 | **0x05** | **0x01** 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x6 0xE9 0x14 0x85 | (20 MHz)

8.9. Update camera operating system TOFCOS

TOFCOS update can be done on site. ESPROS provides a TOFCOS "file" as part of the "TOFCAM635_SW_Package" on the website www.espros.com.

Important:
The upgrade will delete the calibration data. Therefore, first, read back the calibration data from the camera (refer to Chapter 8.8.2.). After the TOFCOS update, restore the calibration data back again to the device (refer to Chapter 8.8.5.).

The command sequence according Table 24 must be executed to upload the latest release of the TOFCOS to the camera.

The following example of a TOFCOS update file with 16 bytes is used in the table below (No valid file, for demonstration purposes only):

`0x10 0x4A 0x56 0x50    0xFF 0x67 0xA0 0xC0    0x23 0x45 0xAA 0x00    0x34 0x78 0x99 0xBB`

Application action	Device reaction	Device answer
Send command "JUMP_TO_BOOTLOADER": | 0xF5 | **0x44** | 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 | 0x19 0xBF 0x6E 0x3C |	Jump to boot-loader	ACK
1st step, send command "UPDATE_TOFCOS" with the control byte "0x00", the password and the size of the update file: | 0xF5 | **0x45** | **0x00 0x21 0x43 0x65 0x10 0x00 0x00 0x00** | 0xBF 0x90 0xC2 0x9F |	Start update: Verify password and store file size	ACK
2nd step, send the command "UPDATE_TOFCOS" with the control byte "0x01", the index and 4 bytes of the "update file". Repeat this step as often as needed = Update file size / 4, e.g. with given update file above: | 0xF5 | **0x45** | **0x01 0x00 0x00 0x00 0x10 0x4A 0x56 0x50** | 0x1C 0x41 0xAC 0x14 | | 0xF5 | **0x45** | **0x01 0x04 0x00 0x00 0xFF 0x67 0xA0 0xC0** | 0x19 0xEE 0xB7 0x69 | | 0xF5 | **0x45** | **0x01 0x08 0x00 0x00 0x23 0x45 0xAA 0x00** | 0x4D 0x59 0x58 0x4B | | 0xF5 | **0x45** | **0x01 0x0C 0x00 0x00 0x34 0x78 0x99 0xBB** | 0x31 0x9F 0x07 0x08 |	Write update: Store data Store data Store data Store data	 ACK ACK ACK ACK
3rd step, send command "UPDATE_TOFCOS" with control byte "0x02": | 0xF5 | **0x45** | **0x02 0x00 0x00 0x00 0x00 0x00 0x00 0x00** | 0x69 0x85 0x52 0x7C | Boot-loader sends acknowledge	Complete update: Verify data	ACK
Boot-loader enforces auto-reset. Wait until the end of the boot time.	Return to regular operation	---
The device is now ready to operate. Communication may be tested with the command "IDENTIFY".	---	---

Table 24: Update procedure

Notes:
- If an error occurs (e.g. corrupted data, invalid command), the device answers with NACK.
- If the update procedure is interrupted, no valid TOFCOS is in the camera memory. Thus, the TOFcam-635-S stays in boot-loader mode. In such case, the update procedure must be restarted. It can be repeated as many times as needed.

9. Maintenance and disposal

9.1. Maintenance

The device does not need any maintenance. A functional check is recommended each time the device is taken into operation:

- Check the mounting position and the detection area of the sensor with respect to the operational conditions. Also check that there is no hazardous situation.
- From time to time, clean the lens with a soft towel like you clean your sunglasses. Never use any solvents for cleaning. THE DEVICE CAN BE DESTROYED!

9.2. Disposal

Disposal should be done using the most up-to-date recycling technologies for electronic components according to the local regulations and laws. The design and manufacture of the cameras and components are done in compliance with the RoHS legal regulations. Traces of dangerous materials may be found in the electronic components, but not in harmful quantities.

10. Addendum

10.1. Related documents

Datasheet epc635, ESPROS Photonics Corp.
Book 3D-TOF, A guideline to 3D-TOF sensors that work by ESPROS Photonics Corp. (author Beat Dede Coi et. al.)

10.2. Links

www.espros.com
www.doxygen.nl
www.graphwiz.org
www.opencv.org - OpenCV (OpenSource Computer Vision)
www.pdal.io - Point Data Abstraction Library (PDAL)
www.pointcloud.org - Point Cloud Library (PCL)
www.qt.io – Application development framework (QT)
www.ros.org - Robot Operating System (ROS)
http://wiki.ros.org - ROS documentation

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ROS	www.ros.org	Open Source Robotics Foundation

Table 25: Licensed open sources used

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