heliCam^{TM} C4 - User Manual

Heliotis AG

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CONTENTS

CHAPTER

ONE

INTRODUCING THE HELICAM™ C4 LOCK-IN CAMERA

The heliCam™ C4 lock-in camera enables rapid and massively parallel dual-phase demodulation of optical signals. The centerpiece of the camera is a custom-designed CMOS image sensor, the heliSens™ S4. It has analogue signal processing circuitry integrated into each pixel sensor unit cell; an approach known as *smart pixel* technology. This way, the sensor addresses the two major constraints of conventional image sensors when used for lock-in applications: frame rate limitations and insufficient dynamic range. The former curbs the maximum demodulation frequency and the latter hampers the acquisition of signals with large offset but small modulation amplitude.

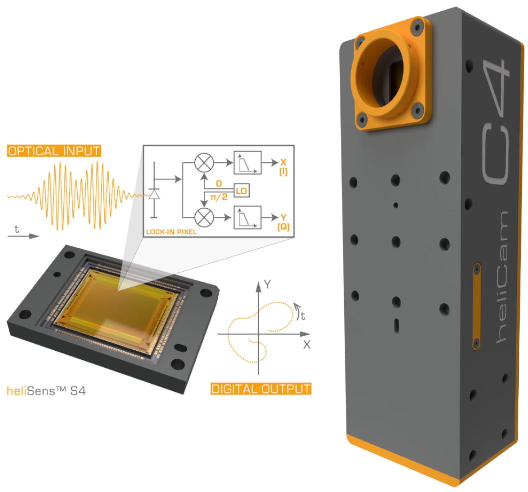


Fig. 1.1: heliCam™ C4 Lock-In Camera

1.1 Outline

This user manual has four main parts:

- *A) Set Up*

  Hardware and Software Commissioning Guide

- *B) Get Started*

  Tutorial for a First Lock-In Measurement

- *C) Basics of Application Software Development*

  Lock-In Camera Operation from a Programming Environment

- *D) Advanced Concepts and Control*

  Detailed Discussion of Available Settings and the Measurement Signal

1.2 Specifications

Table 1.1: heliSens™ S4 - Lock-In Pixel Image Sensor

<table>
<tr><th>Feature</th><th colspan="5">C4.0-S40</th><th colspan="5">C4.0-S40U</th><th colspan="5">C4.0-S41U</th><th colspan="5">C4M.0-S4M0</th></tr>
<tr><td>Number of Pixels</td><td colspan="15">512 x 542</td><td colspan="5">1024 x 1102</td></tr>
<tr><td>Pixel Size</td><td colspan="15">24 µm $\times$ 24 µm</td><td colspan="5">12 µm $\times$ 12 µm</td></tr>
<tr><td>Fill factor</td><td colspan="5">21%</td><td colspan="10">55% with micro-lens array (angular aperture ± 12°)</td><td colspan="5">23%</td></tr>
<tr><td>Full Well Capacity</td><td colspan="10">500 ke^-</td><td colspan="5">125 ke^-</td><td colspan="5">70 ke^-</td></tr>
<tr><td rowspan="2">Quantum Efficiency</td><td colspan="2">nm</td><td colspan="2">400</td><td colspan="2">450</td><td colspan="2">500</td><td colspan="2">550</td><td colspan="2">600</td><td colspan="2">650</td><td colspan="2">700</td><td colspan="2">750</td><td colspan="2">800</td></tr>
<tr><td colspan="2">%</td><td colspan="2">61.7</td><td colspan="2">73.1</td><td colspan="2">78.7</td><td colspan="2">78.6</td><td colspan="2">74.9</td><td colspan="2">72.9</td><td colspan="2">69.4</td><td colspan="2">58.4</td><td colspan="2">45.5</td></tr>
<tr><td>Detection Threshold

f_{ref} , T</td><td colspan="20">P_{min} in $\frac{\text{mW}}{\text{m}^2}$

, at a given reference frequency, f_{ref}, and filter time constant, T</td></tr>
<tr><td>1kHz, 10ms</td><td colspan="5">1.03</td><td colspan="5">0.34</td><td colspan="5">0.14</td><td colspan="5">1.2</td></tr>
<tr><td>10kHz, 1ms</td><td colspan="5">10.3</td><td colspan="5">3.4</td><td colspan="5">1.4</td><td colspan="5">12</td></tr>
<tr><td>100kHz, 1ms</td><td colspan="5">33.3</td><td colspan="5">10.9</td><td colspan="5">4.2</td><td colspan="5">NA</td></tr>
</table>

Table 1.2: heliCam™ C4 - Lock-In Features

Feature		Internal Reference	External Reference
Number of parallel, dual-phase Demodulators	C4	277 504	
	C4M	1 110 016	
Reference Signal		reference **pulse** wave with adjustable duty cyle (causing residual sensitivity to odd harmonics of the reference frequency)	
Reference Frequency, f_{ref}	C4	305 Hz - 135 kHz	≤ 135 kHz
	C4M	305 Hz - 50 kHz	≤ 50 kHz
Frequency Resolution		$\Delta f_{ref} \approx 5 \cdot 10^{-8} \cdot f_{ref}^2$	quarter period trigger registered with 80 MHz clock rate
Phase Resolution		0.1 deg	
Filter Time Constant	C4	0.25 ms - 325 ms	≥ 0.25 ms
	C4M	0.8 ms - 100 ms	≥ 0.8 ms
Number of Frames per Acquisition	C4	4 - 900	
	C4M	4 - 225	
Output Data		amplitude & phase / in-phase & quadrature	
Dynamic Range		2×10 bit (X, Y)	
Background Suppression / AC Coupling	C4	21 bit equivalent	
	C4M	18 bit equivalent	

Table 1.3: heliCam^{TM} C4 - Interfaces

Software	Software Development Kit	GenICam producer DLL
		GenICam producer DLL with examples for Python, MATLAB^{TM} LabVIEW^{TM}, C++ and .NET
	heliViewer^{TM} Application Software	GUI based application for camera control, data acquisition, visualization, and storage
Electrical	Control Signal and Data Transfer	Gigabit Ethernet
	LIA Module	reference input and acquisition trigger with adjustable phase delay
		internal reference output
		other in- and output signals
	Configurable Modulated Test Signal	sine wave (continuous/bursts)
		50 kHz maximum frequency
		adjustable DC
		electrical output via SFIO
		optical output via LED module
	Peak Power Consumption	24 VDC, 30 W
Mechanical	Objective	detachable C-mount
	Mounting	M6 holes (front, left, right, top)

Table 1.4: heliCam™ C4 - Temperature Control

Feature	C4x.0-S4x	C4x.0-Sx + HSFC4.1
Cooling Option	user provided cooling, e.g., mounting on heat sink	forced convection with on- and off switch
Dimensions	46 × 65 × 180 mm ^{3}	67 × 65 × 180 mm ^{3}
Mass	850 g	1150 g
Permissible Ambient Temperature	depends on the cooling setup	0 - 40 ° C

Note: These values reflect currently available settings. Possible discrepancies with respect to the heliCam™ C4 data sheet are due to software limitations. Freely installable updates will overcome these in the future. Get in touch with Heliotis support for more information.

CHAPTER TWO

A) SET UP

This chapter guides you through the process of connecting hardware components and installing software to make the heliCam^{TM} C4 ready for use.

2.1 Hardware Installation

A pre-requisite for its operation is that heliCam^{TM} C4 is properly powered, temperature-regulated and wired to control elements. The following hardware setup guide lays out how the camera is installed, and which precautions must be observed to prevent damage.

2.1.1 Package Contents

The recommended order of the heliCam^{TM} C4 package includes several hardware accessories:

- 1x heliCam^{TM} C4 Lock-In Camera
- 1x heliDriver^{TM} D3 Power Supply, Interface, and Illumination Control Unit (LIA Module)
- 1x AC/DC Switching Adapter with 24V DC, 60W Output for Power Supply to the heliDriver^{TM} D3
- 1x LED Module with Integrated Cable (beige) and Connector to generate Test Inputs
- Interconnecting Cables:
  - 1x GigE Cable (green)
  - 1x Connecting Cable (gray)
  - 2x BNC-BNC Cable (black)

Note: If the contents of the package are incorrect, insufficient, or damaged in any way, contact Heliotis or your local distributor.

2.1.1.1 heliCam^{TM} C4

In this document, the term *heliCam™ C4* refers to the physical camera, which performs in-pixel lock-in amplification of optical signals. Several elements on its surface are important for its installation and operation or are prone to damage if handled improperly (see Fig. 2.1). Hereafter, each of them is elaborated on.

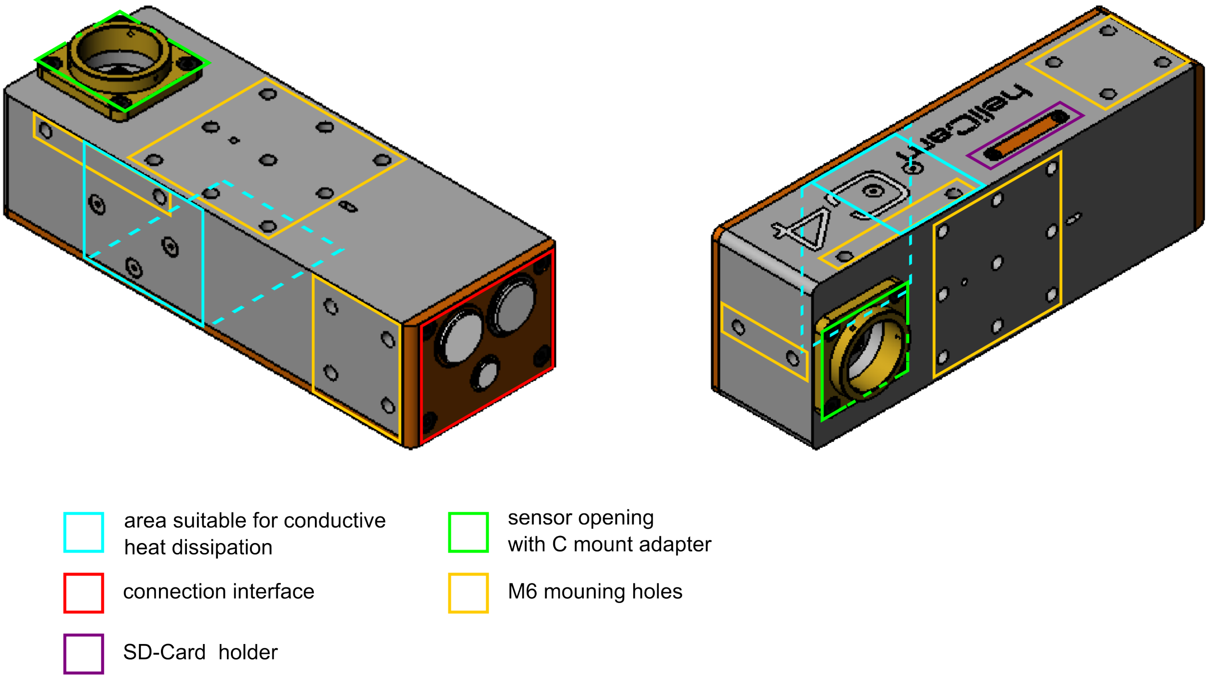


Fig. 2.1: heliCam™ C4 Exterior

2.1.1.1.1 Thermal Requirements

Important: At room temperature and under standard operating conditions, the heliCam™ C4 requires cooling.

The heliCam™ C4's power consumption is 25-30 W. Its surface area is too small for passive cooling by the surrounding air to dissipate the generated heat fast enough without additional measures. With this cooling effect alone, the camera's core temperature will eventually exceed the scope of valid values, which is below 85 °C. Overheating may cause operational instabilities and ultimately leads to a safety shutdown.

An integrated, fan-based cooling accessory is available (see Fig. 2.2). It suffices at ambient temperatures ≤ 40 °C. When mounting a heliCam™ C4 equipped with this accessory, make sure that air can be aspired and discharged without obstruction. The fans may be switched off temporarily, e.g., before taking very vibration-sensitive measurements. This prevents any interference that could be caused by the cooling mechanism.

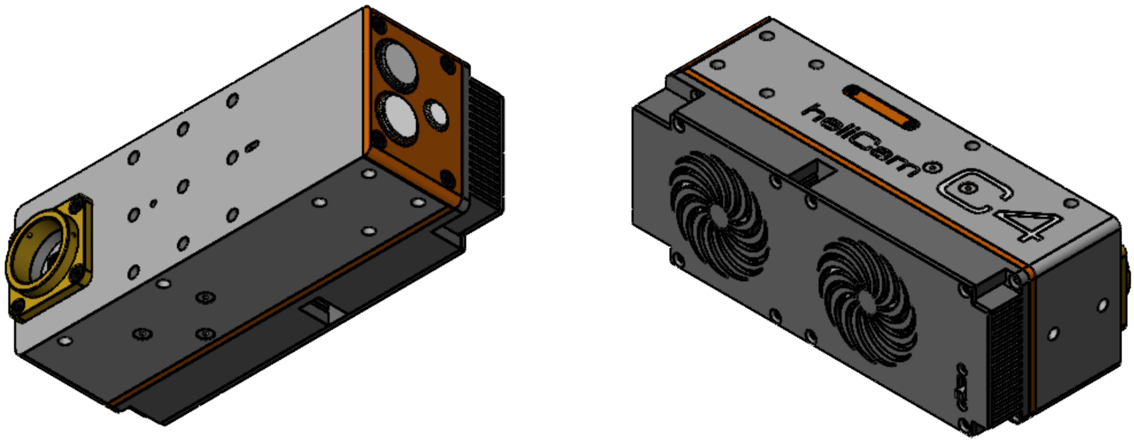


Fig. 2.2: heliCam™ C4 with HSFC4.1 Cooling Accessory

If the accessory for temperature control is not purchased, it is the user who must provide external cooling to the lock-in camera. Although the choice of cooling system is ultimately up to him or her, its heat dissipating capacity must be at least equivalent to that of either of the following measures:

- at ambient temperatures ≤ 40 °C, an airflow ≥ 1.5 m^3/min ≈ 45 CFM can be provided to the heliCam™ C4. This condition is met by most fans with at least 40 mm diameter when operated at 12 VDC.
- the heliCam™ C4 may be thermically well-connected to a heat sink with a thermal resistance < 0.65 K/W, e.g., an aluminum surface > 0.14 m^2 with a recommended length / cross-section ratio < 50 m^{-1}. The areas most suitable for dissipating heat by conduction are marked in Fig. 2.1.

2.1.1.1.2 Sensor Opening

The lock-in camera's light-sensitive zone - the front of its image sensor - is located within a shallow cavity, as shown in Fig. 2.1. The heliCam™ C4 opening has a C mount. By way of these standardized screw threads, corresponding objectives may be affixed at a normed distance from the sensor.

During shipment, the cavity containing the image sensor is sealed either with a screwed-on cap or, if commissioned, the LED module. Upon arrival, the latter is thus already correctly placed for the starter experiment described in the next section, *B) Get Started*. Eventually, either cover will have to be removed before acquiring images of the ultimate object of interest.

Important: There is no additional protective layer on the sensor. **So be careful not to contaminate or damage the image sensor once it is exposed.** The cap may be reattached when the camera is not used for prolonged periods to protect the sensor from dust and damage.

The sensor's photoactive area is cleaned before shipping. **If the sensor gets dirty during use, contact** Heliotis support**. Do not proceed with cleaning the sensor on your own before you receive precise instructions and apply the utmost caution when you clean it under the guidance of the support team.**

2.1.1.1.3 Connection Interface

The bottom of the heliCam™ C4 contains an interface with three color-coded connectors (see Fig. 2.3):

1. An 8 Pin acquisition control and data transfer connector (grey) for linking the camera to a computer by means of a Gigabit Ethernet (GigE) cable (green). Its counterpart lies at the grey coated end of said cable.
2. A 19 Pin Power Supply and I/O connector (orange), for wiring the camera to the heliDriver™ D3. The corresponding end of the Connecting Cable (grey) has an orange coat.
3. A 2 Pin output connector (green) for relaying a modulated signal originating from the heliDriver™ D3 to the LED module. The LED module can be attached with the green coated end of its cable.

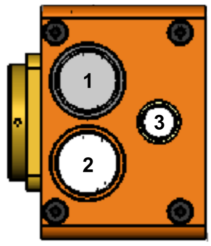


Fig. 2.3: heliCam™ C4 Connection Interface

2.1.1.1.4 Mounting Holes

In an experimental setup, the camera's position may be fixed by means of dedicated M6x1.0 mm - 6H mounting holes (9 x ↓ 4 mm on the front, 6 x ↓ 5 mm on left and right faces each, 2 x ↓ 4 mm on top, see Fig. 2.1 and technical drawings in *Annex*).

2.1.1.1.5 SD Card Opening

The heliCam™ C4 stores its file system on an SD card, which is located underneath a screwed-tight cover (see Fig. 2.1).

Note: If you suspect that the SD card is corrupt, please contact Heliotis support to receive guidance on how to rewrite its contents. **Do not unseal the SD card opening unless explicitly instructed to do so by the Heliotis support team.**

2.1.1.2 heliDriver™ D3

The heliDriver™ D3 is a connection module, which supplies power to the lock-in camera. Moreover, it optionally serves as a communication interface to feed in and process external control signals, as well as to read out camera and sensor status information in real time. The illumination of the accessory LED module can be controlled from the heliDriver™ D3 too.

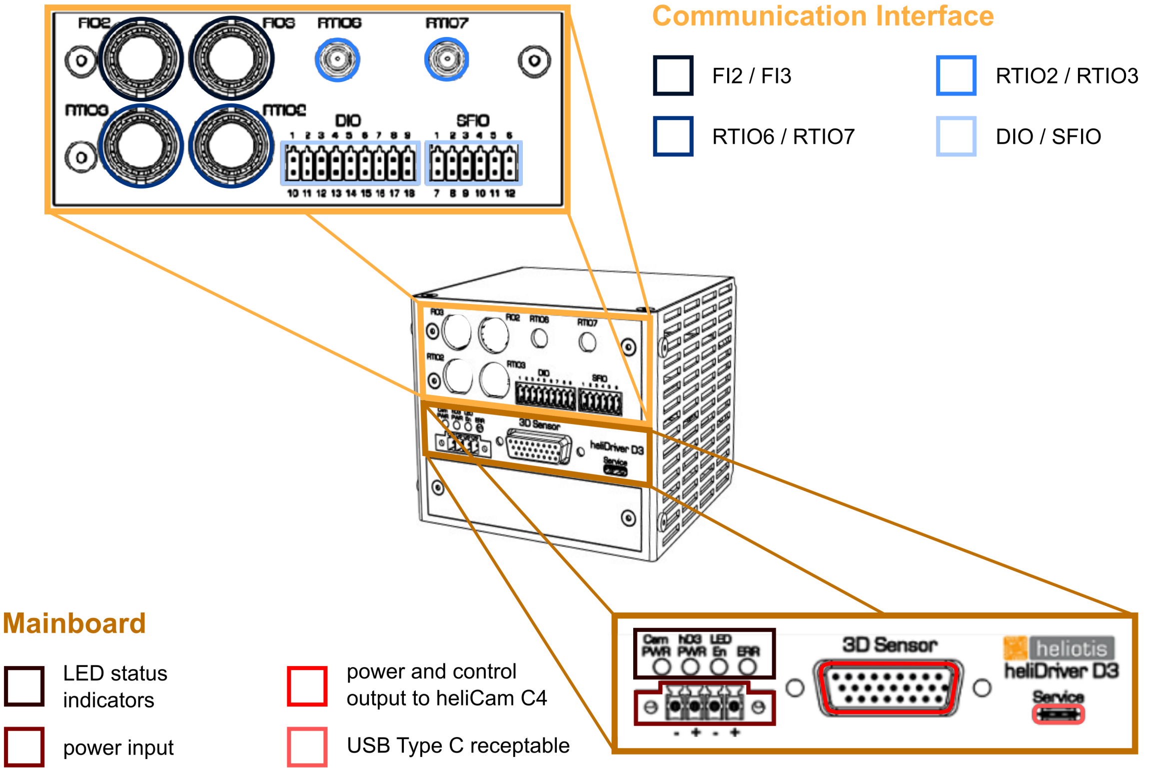


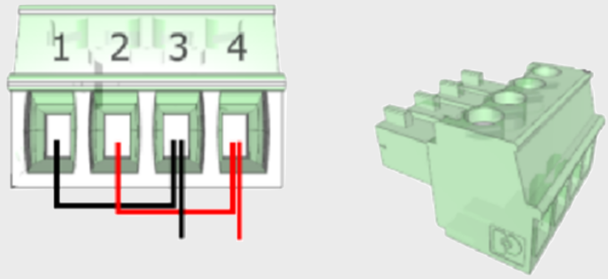
Fig. 2.4: heliDriver™ D3 Front Panel with Mainboard and Communication Interface

2.1.1.2.1 Mainboard

The heliDriver™ D3 requires a 24 VDC, 60 W input via its main board (see Fig. 2.4). This can be ensured by connecting it to a 115/230 VAC socket via the AC/DC switching adapter included in the standard shipment. A power cable with C13 coupling for the adapter must be procured separately by the user.

The AC/DC switching adapter included in the standard delivery comprises a counterpart to the power input connector (see Table 2.1). Located just above this input connector are four LED status indicators, providing *useful feedback* on the state of hardware components once the setup is powered.

Table 2.1: heliDriver™ D3 Power Supply Connector Pin Assignment



Pin	Terminal designation	Details
1	GND	Camera GND
2	V_{DD}	Camera supply 24 V
3	User GND	Camera User GND and heliDriver™ D3 GND
4	User V_{DD}	Camera User supply and heliDriver™ D3 supply 24 V

The Connecting Cable (grey) fits the D-Sub connector for power supply and signal transmission to the lock-in camera on the heliDriver™ D3's main board. In addition, the heliDriver™ D3 offers surge, reverse polarity, and transient protection to the camera.

2.1.1.2.2 Communication Interface

For many lock-in applications it is desirable to synchronize the data acquisition and demodulation with external control signals. For this purpose, the heliDriver™ D3 offers a communication interface (see Fig. 2.4).

- Trigger signals to activate the recording or to time the demodulation sequence in the image sensor, such as the external reference signal, are most conveniently delivered to the camera via the inputs FI2/FI3 (with BNC connectors) and RTIO6/RTIO7 (with SMA connectors). **External triggers should be rectangular signals with 0 V minima 5 V and maxima.**
- Synchronization, debugging or monitoring may require reading back status signals from the camera in real time. For this purpose, outputs RTIO2 and RTIO3 are the preferred connectors. **Note that output signals from the camera have a fixed latency of ~ 1 µs.**

With the BNC-BNC cables included in the standard delivery, these inputs and outputs can be connected to other elements of your experimental setup or to electronic test equipment.

Alternatively, DIO and SFIO pins can be used to input and output signals at the cost of a reduced transmission speed. For the (default) DIO and SFIO pin assignment see the heliDriver™ D3 data sheet, Section Lock-In Amplifier Module.

2.1.1.2.3 Illumination Control

The heliDriver^{TM} D3 that comes with the heliCam^{TM} C4 comprises an internal, software-controlled signal generator. This unit allows you to create an electrical sine wave in a user configurable fashion to drive the Heliotis LED module included in the standard delivery.

2.1.1.3 LED Module

The LED module - when fed via the heliCam^{TM} C4 with electric control signals generated by the heliDriver^{TM} D3 - can be used to generate simple, well-controlled, amplitude-modulated optical signals. Even if you ultimately do not need such input signals in your research, the LED module should be useful when getting familiar with the lock-in camera and testing your setup.

2.1.1.4 Interconnecting Cables

The three cable types included in the standard shipment are respectively used for the following:

- GigE Cable (green): relaying software control commands to the heliCam^{TM} C4 and fast transmission of measurement data back to the lab computer.
- Connecting Cable (gray): power supply of the heliCam^{TM} C4 and transfer of control signals between heliDriver^{TM} D3 and heliCam^{TM} C4.
- BNC-BNC Cable (black): communication of time-continuous control signals from and to non-Heliotis elements of the experimental set up via the heliDriver^{TM} D3.

2.1.2 Wiring

Fig. 2.5 summarizes schematically how the heliCam^{TM} C4 and its accessories are wired together. To get started, join the contents of the shipment accordingly.

Important: For safety reasons, power the ensemble only after all individual pieces are connected.

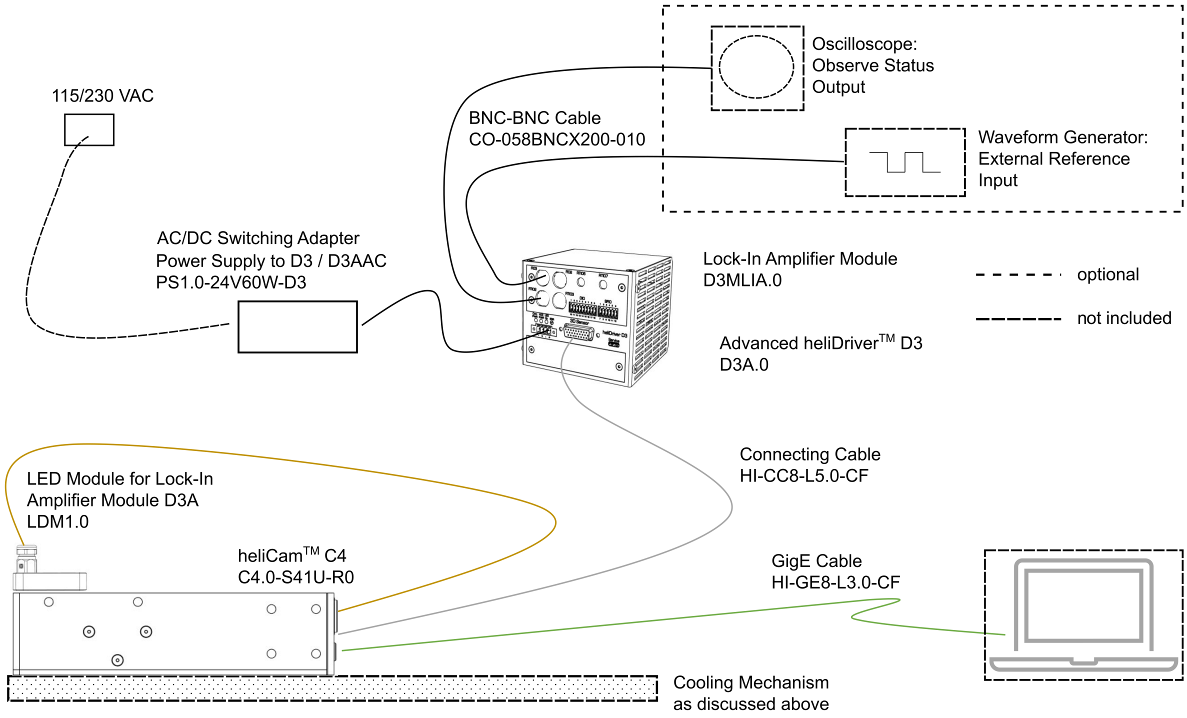


Fig. 2.5: Wiring of the heliCam™ C4 with Components of the Standard Delivery Package

2.1.3 Checking the Hardware Setup

When you are done, the LED status indicators on the heliDriver™ D3's mainboard allow you to check if the heliDriver™ D3 and the heliCam™ C4 are properly powered and can communicate with one another. After switching on these devices, they will boot for a few seconds. In the process, the LED designated "Cam PWR" should go from initial yellow to green, indicating the camera is powered and ready (see Fig. 2.6).

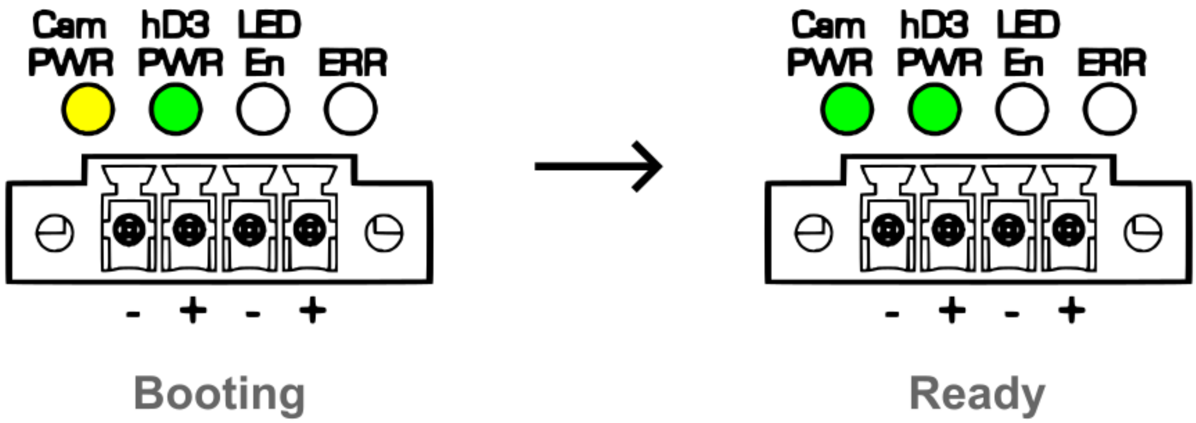


Fig. 2.6: heliDriver™ D3 LED Status Indicators during and after Booting

Note: If "Cam PWR" does not turn green or the error indicator "ERR" stays on, check the wiring. Should the problem be persistent when you switch the power supply off and on again, contact Heliotis support. Please report the state of the LED status indicators when you reach out to the support team to ensure that you receive focused help right from the start. For the detailed meaning of individual LED status indicators, you may consult the heliDriver™ D3 data sheet.

2.2 Software Installation

Here, you are introduced to Heliotis software for the heliCam™ C4 and receive instructions on how to download as well as install it on the computer, which you connect to the lock-in camera. With this software, the heliCam™ C4 can be operated in different ways.

- A software development kit (SDK) with usage examples, allows you to control the heliCam™ C4 from most common programming platforms, such as Python, MATLAB™, or LabVIEW™.
- To get started and for simple validation tasks, the proprietary heliViewer™ application is the recommended and simple-to-use alternative to more powerful, but rudimentary, developing environments. It is a LabVIEW™-based program, built upon the SDK, that features a graphical user interface (GUI) to command the heliCam™ C4.

2.2.1 Software Organization and Integration Options

A brief overview follows, outlining the contents and organization of the software provided by Heliotis and its interfaces with third party software (see Fig. 2.7) in more detail.

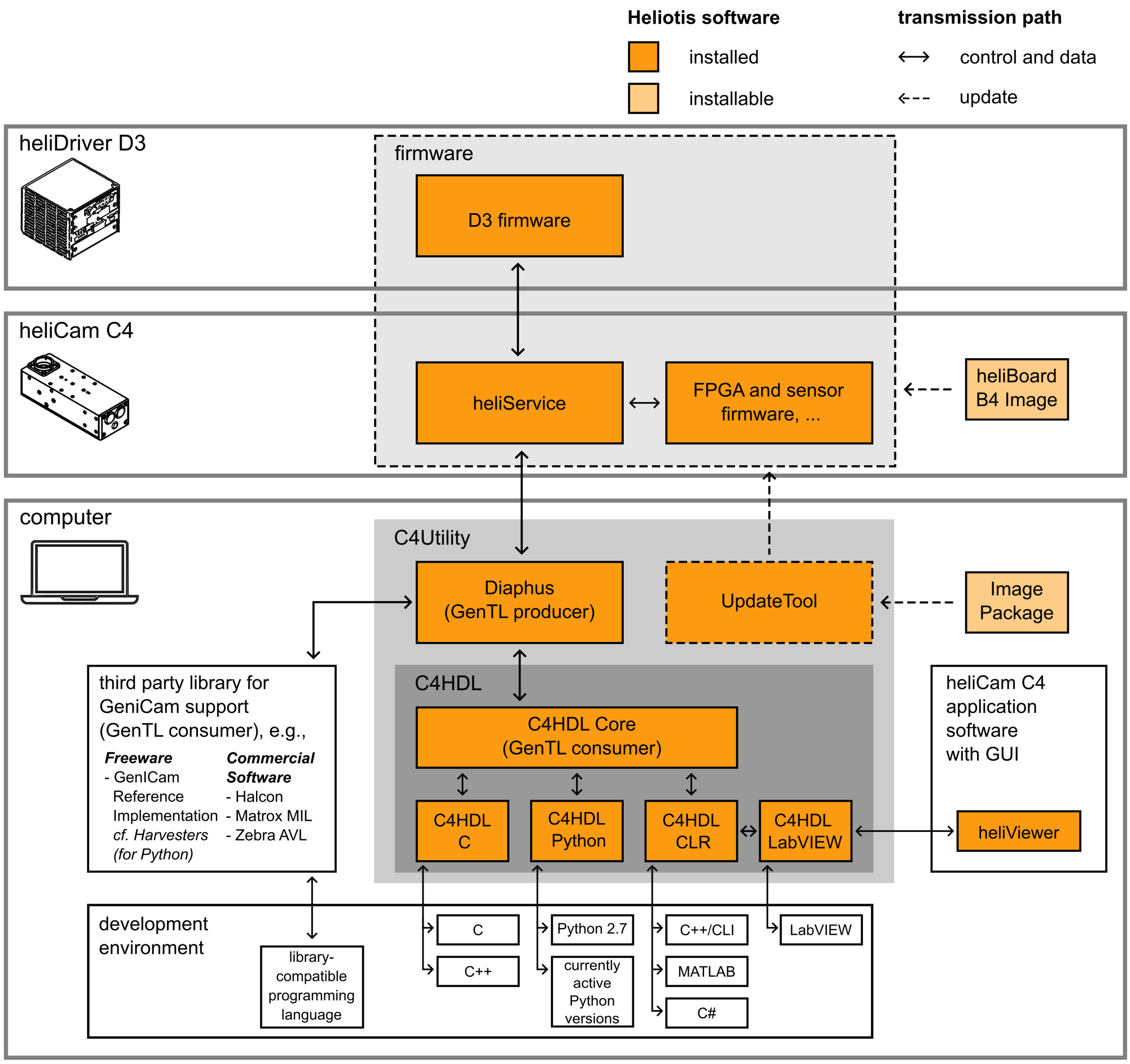


Fig. 2.7: Overview of Heliotis Software

2.2.1.1 Firmware

A set of programs, preinstalled before shipment and collectively named firmware, operate on the Heliotis hardware itself, i.e., the heliCam™ C4 and the heliDriver™ D3. In particular, the heliCam™ C4 runs a special Linux version, with a custom-written service. This service, handling the lock-in camera at a low level, is called heliService. No direct user interaction with heliService is envisaged.

2.2.1.2 Software Development Kit

The communication with heliService is managed by Diaphus, a Heliotis driver software for the connected computer. Diaphus provides a normed interface for controlling machine vision cameras. It complies with the industrial Generic Interface for Cameras (GenICam) consortium standard, which is administered by the European Machine Vision Association (EMVA). More precisely, Diaphus is what is called a GenTL *producer* within the GenICam framework.

Two principal options for using the heliCam™ C4 through this generic camera interface are supported:

1. The heliCam™ C4 can be operated using the GenICam interface directly without intermediary software from Heliotis. You can access measurement data and all configurable or readable camera parameters from any environment with a so-called GenTL *consumer* implementation.
   - For some programming languages, such as C++, Java, and Python, third party libraries are freely available, that include such a GenTL consumer. Notable are in particular the official reference implementation from GenICam and its user-friendly spin-off for Python, Harvesters, which is available through pip.
   - In addition, commercial machine vision software often supports GenICam compliant cameras, e.g., MVTec Halcon, the Matrox™ Imaging Library (MIL) and Aurora™ Vision Library (AVL) from Zebra. This list is neither exhaustive, nor does it imply a Heliotis recommendation for these programs.
   - If you are already familiar with GenICam, you may even wish to implement a GenTL consumer yourself.
2. You can also control the heliCam™ C4 via the C4 Handler Library (C4Hdl) from Heliotis. The C4Hdl provides a simplified and reduced Application Programming Interface (API) that is proprietary. The core of the C4Hdl is a C++ wrapper around Diaphus. It underlies several libraries, each of which enables you to interact with the heliCam™ C4 in different programming environments. Currently, Dynamic-Link Libraries (DLL) are available in C, Common Language Runtime (CLR) for .NET programs, Python, and LabVIEW™. Wrapped in this form, libraries can be easily imported into the targeted user application. With this second option, the same camera parameters are accessible as with the first one and the overhead is minimal.

Diaphus, the C4 Handler Library and examples of their use in different programming languages form the software development kit, which is aiding you in the development of application programs for the heliCam™ C4.

2.2.1.3 updateTool

Heliotis firmware is subject to active further development. Updates make new features available and fix bugs. The GUI-based program updateTool is available to manage comfortably firmware versions installed on the heliCam™ C4 and the heliDriver™ D3 from the connected computer. The updateTool is also useful to *check your software set up*.

2.2.1.4 C4Utility

The SDK applications on the computer side, along with the updateTool, are grouped together into a single package named C4Utilitiy.

2.2.1.5 heliViewer™

The application software heliViewer™ is used to control camera and illumination parameters through a GUI, as well as to acquire, visualize and store data. It is not a tool for software development, however. The heliViewer™ uses the C4Hdl wrapper library for LabVIEW™ and must be installed on top of the underlying software development kit.

2.2.2 Heliotis Software Download

On the Heliotis website under Support/Downloads, you find the most recent firmware, C4Utility package and heliViewer™. To gain access, you must register once (see Fig. 2.8) and wait for your account to be approved.

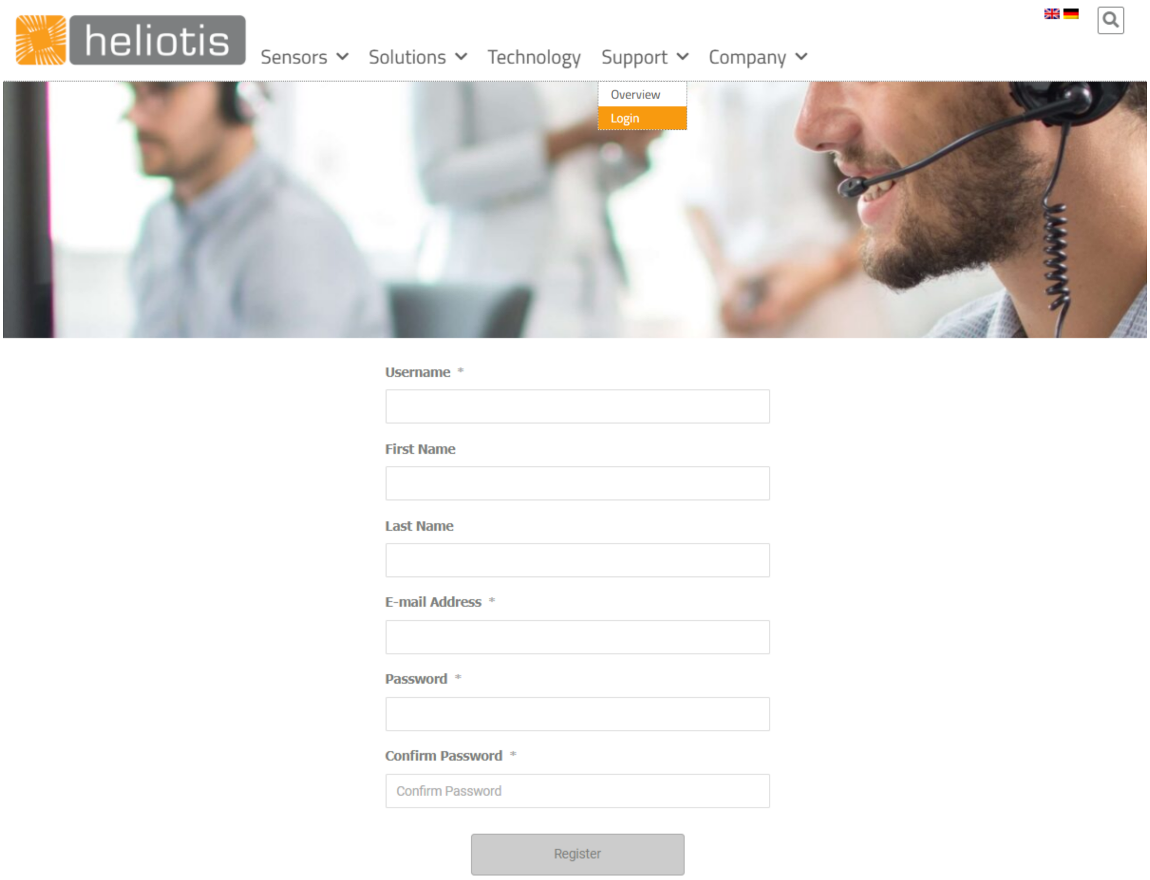


Fig. 2.8: Heliotis Account Registration for Software Download

You receive the heliCam™ C4 with the latest version of the firmware installed at the time of shipment. For the first commissioning, you will therefore just need to download the computer-side applications; C4Utility and optionally the heliViewer™. The description of the starter experiment in the next section, *B) Get Started*, is based on the (full version of the) heliViewer™ (for Heliotis devices of the latest generation), which you therefore might want to install. Alternatively, you can get started directly in Python with the help of an illustrative *Jupyter Notebook* you receive as part of C4Utility. Make sure you download a version of the Heliotis software which is compatible with your operating system.

Later, you may wish to download (updated) firmware and install it on the Heliotis hardware. It is available in two forms:

- as an Image Package to upgrade the firmware on your heliCam™ C4 through updateTool once a newer version is released.
- as a heliBoard B4 image, the way it is stored on an *SD card* within the heliCam™ C4. The firmware is only needed in this format if the Heliotis support team explicitly instructs you to overwrite a corrupt file system on the heliCam™ C4.

At the same location, you find a changelog informing you about changes between versions and bug fixes.

2.2.3 Installing C4Utility and heliViewer™

After you downloaded the Heliotis software, install C4Utility by running the executable "C4Utility*.exe" and following the instructions of the installation wizard. If you decided to install the heliViewer™ as well, do so by unzipping its installation folder and running "setup.exe". Make sure you install heliViewer™ after C4Utility. As explained above, the latter provides the drivers and interface libraries for communication with the heliCam™ C4, which heliViewer™ relies on. Please restart the computer when the installation is complete.

2.2.4 Establishing Network Connection

The heliCam™ C4 is connected to the host computer via Ethernet in a local area network. To exchange control commands and data, the heliCam™ C4 and the computer must locate each other within this network.

2.2.4.1 Configuring the Host Ethernet Adapter's IP-Address

The heliCam™ C4 and the host use the internet protocol suite, TCP/IP, to communicate with each other. These devices therefore need an identifier called IP address. In private networks, as is the case here, IP addresses are not routed on the Internet. Thus, they need not be coordinated with an IP address registry. But within the confines of the private network, each device's IP address needs to be unique to avoid ambiguity. Additionally, the IP addresses of the heliCam™ C4 and host must specify that they are both found in the same subnet. The two conditions are usually not met by default.

To ensure these requirements are satisfied, you may manually configure the IP address of the host computer's Ethernet adapter, through which it is connected to the heliCam™ C4. By default, the static IPv4 address of the heliCam™ C4 is 192.168.2.71 with subnet mask 255.255.255.0. This subnet mask indicates that the first three octets of bits in the IP address designate the network and only the last octet is used to identify devices within this network. Hence, the first three octets of the host IP address must match the heliCam™ C4's and the last must differ. IP addresses specified in this way lie within a range of IPv4 addresses reserved for private networks. **In short, if you do not change the heliCam™ C4 's default IP address, the host Ethernet adapter must use an IPv4 address of the form 192.168.2.x, where x is an integer between 1 and 254 other than 71 and the subnet mask 255.255.255.0 (see Fig. 2.9).**

2.2.4.2 Configuring Host Security Software

The firewall or other security software may prevent you from opening a connection to the heliCam™ C4 from the updateTool and the heliViewer™. Check that these Heliotis programs are not blocked from interfacing the camera by your computer's security measures. How the Windows firewall can be configured to let updateTool (and by analogy the heliViewer™) communication pass through is depicted in Fig. 2.10.

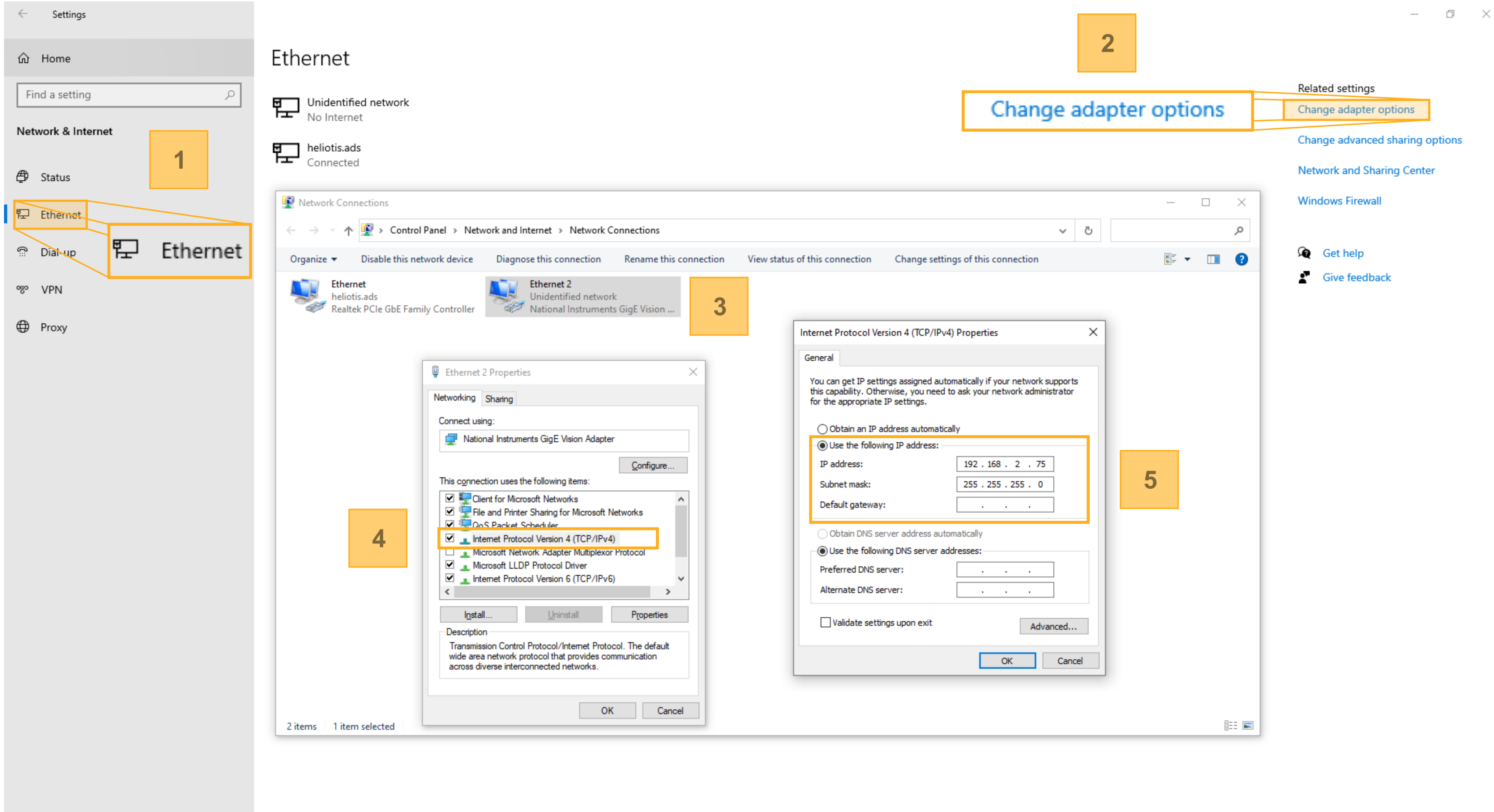


Fig. 2.9: Network Adapter IP Address Configuration

1. Open Network settings. (Start > System control > Network & Internet > Ethernet)
2. Open the dialog “Change settings”.
3. Select network to which the heliCam™ C4 is connected.
4. Open TCP/IPv4 - properties. (We also recommend you disable GigE vision filters if possible since they can interfere with the connection.)
5. Set the IP address to 192.168.2.x (with x=1-70 or 72-254), the subnet mask to 255.255.255.0 and confirm your choice.

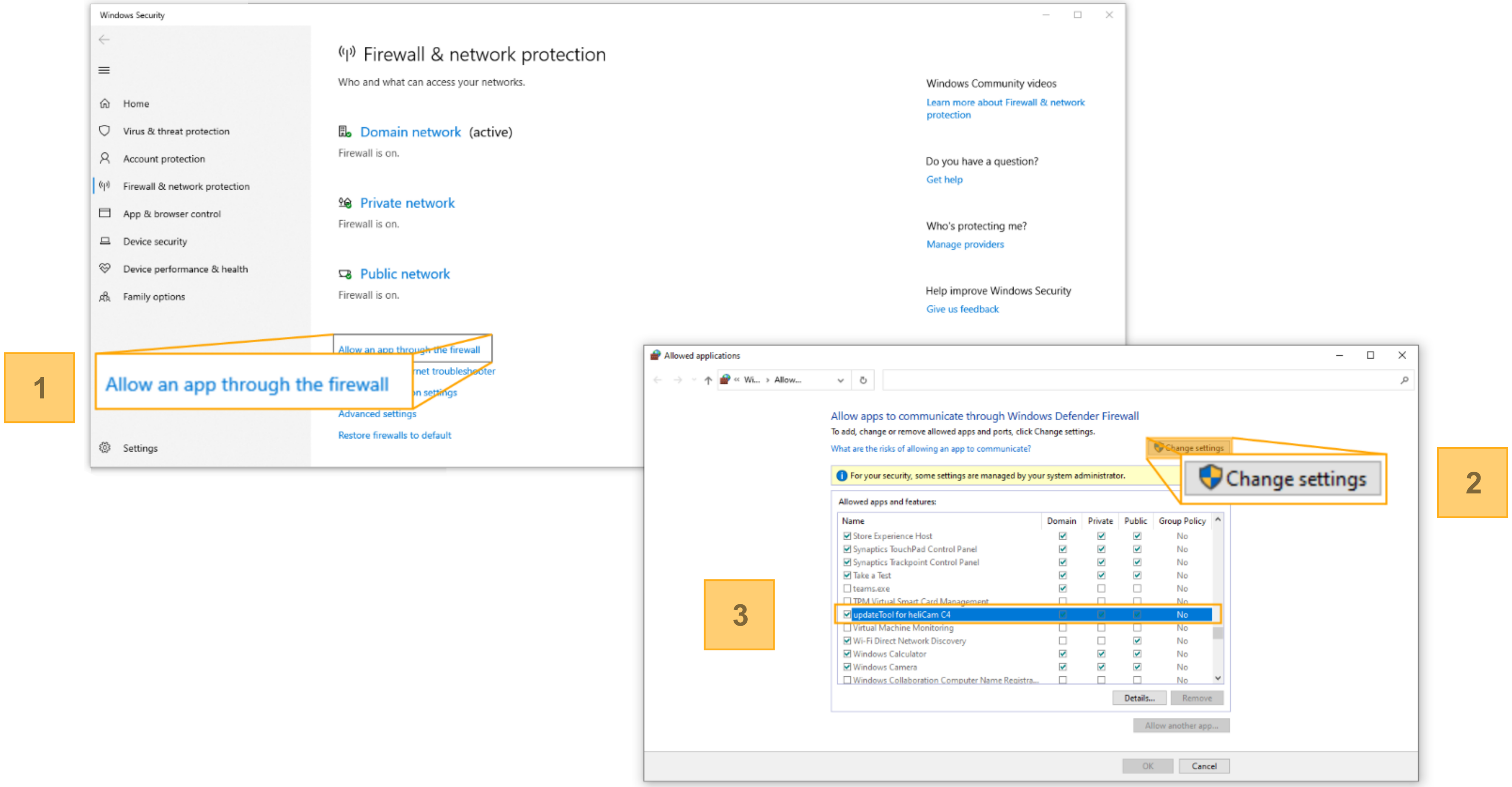


Fig. 2.10: Allowing Apps to communicate through the Windows Firewall

1. In the Windows firewall configuration menu (Start > System Control > Windows Firewall), open the dialog “Allow an app through the Firewall”.
2. Open the dialog “Change settings”.
3. Add authentication exceptions for C4Utility and heliViewer ™
   ⇒ Add exceptions (tick) for public, private and domain networks.

2.2.4.3 Network Interface Controller

Heliotis recommends you use a separate Network Interface Controller (NIC) for the heliCam™ C4 instead of a router and switches. This ensures that the data transmission is faster, as the transmission line is not shared by multiple clients.

2.2.5 Checking the Software Setup

The program updateTool, that *you installed* as *part of C4Utitlity* , allows you to check if the software is set up correctly by verifying:

- if the computer-side driver software is compatible with the firmware on the hardware.
- whether the network connection between host computer and heliCam™ C4 could be properly established.

You may do so by opening the updateTool and pressing the button "Update Device List" to tabulate all available devices in the network (see Fig. 2.11).

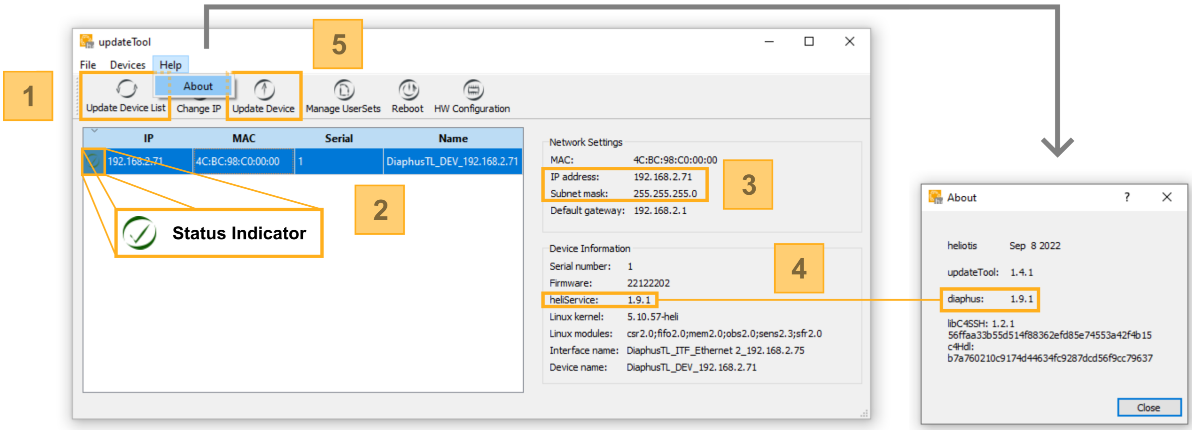


Fig. 2.11: Software Setup Check in updateTool

1. Detect devices in the network using the "Update Device List" button.
2. Select the heliCam™ C4. The status indicator reveals if the camera is ready for use or, if necessary, why it is not. A specific status message is displayed if you hover over the status indicator with your mouse.
3. A network configuration mismatch indicates that the network adapter IP address is not compatible with the heliCam™ C4's, which is marked on the window's right-hand side.
4. The heliCam™ C4 firmware component heliService and the computer-side driver software Diaphus communicate directly with one another. This communication is only successful if their versions match.
5. If necessary, update the selected heliCam™ C4 with an Image Package from the Heliotis download page.

The heliCam™ C4 should then appear along with a color-coded status indicator (see Table 2.2) to the left of its IP address. Your software setup is functional if the status indicator is a check mark. In the contrary case, it is a cross, meaning you must make adjustments. If the indicator's color is orange, there is already an open connection to the camera. The indicator is green if the camera is ready for use, or red otherwise.

Table 2.2: Software Connection Status Indicator in updateTool

Sign	Meaning
	A green check mark indicates that the camera is ready for use.
	An orange check mark stipulates that your setup is functional, and that you already have an open connection to the heliCam™ C4 in some application.
	An orange cross means you are not properly set up to connect to heliCam™ C4 with this computer but that another device in the network has an open connection to it.
	A red cross tells you, that an issue needs to be fixed before you can interact with the camera.

Trouble Shooting

If the camera is not marked ready for use by a green check mark, proceed as follows (see Fig. 2.12):

- An **orange check mark** does not indicate an error per se. If you want to update the heliCam™ C4 or open a new connection, simply close the application program from which originates the open connection or terminate the software connection within it.
- The **orange cross** status indicator becomes a red cross, when closing the program that is accessing the heliCam™ C4 from some device in the network other than the computer running updateTool.
- If the status indicator is a **red cross**, hover over it with your mouse to receive a specific status message.
  - A network configuration mismatch is flagged if the IP addresses of host and heliCam™ C4 are not compatible (see Fig. 2.11).

    ⇒ *Configure the host ethernet adapter's IP address as described earlier.*
  - The connection to the camera cannot be established either if the firmware version on the heliCam™ C4 does not match the Heliotis software version installed on the host computer. The status message tells you in this case that the software versions of the camera-side heliService and computer-side Diaphus do not match (cf. Fig. 2.7).

    ⇒ Install firmware to match C4Utility or vice versa. We recommend installing the latest version of C4Utility and *updating the firmware* accordingly. You can compare the version of the camera-side firmware component heliService (select the camera in the updateTool and the version is displayed on the right-hand side) explicitly with that of the computer-side counterpart Diaphus (found in the updateTool menu under Help/about). This is illustrated in Fig. 2.11.
- If the heliCam™ C4 is not detected at all when pressing "Update Device List", proceed with *checking the hardware setup according to the relevant, foregoing section* and *making sure that your computer's security measures do not prevent updateTool from connecting to the camera*.

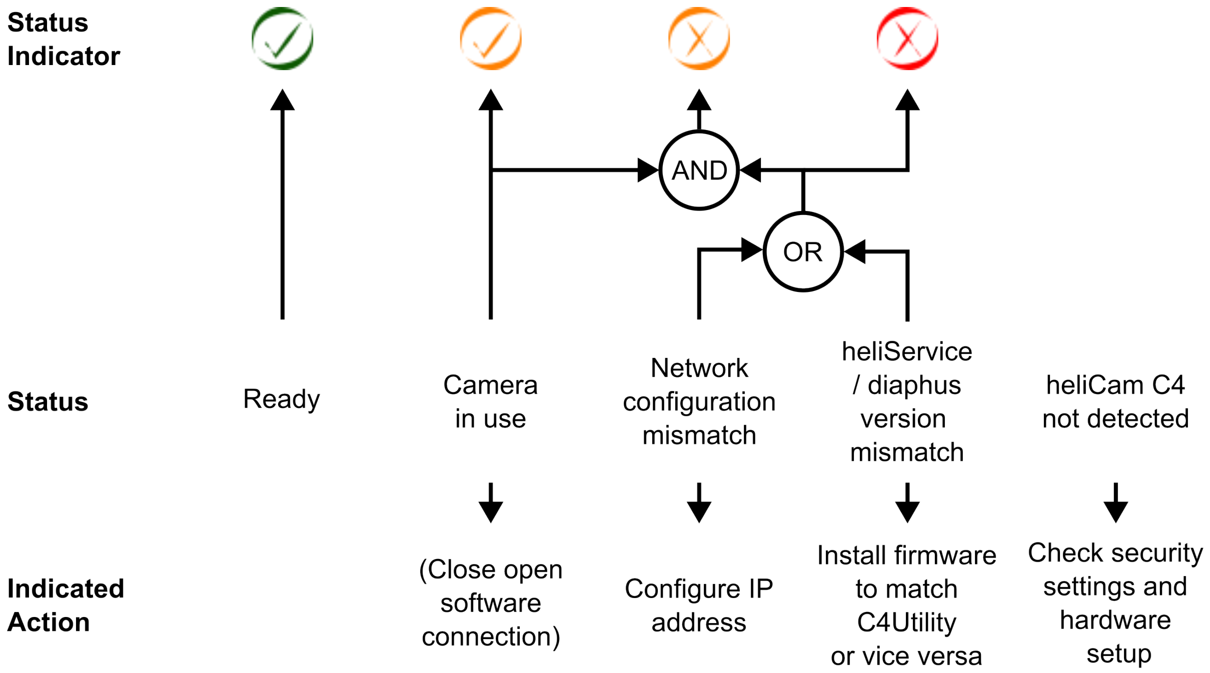


Fig. 2.12: Network Connection Trouble Shooting

2.2.6 Updating Firmware

In addition to verifying your software setup, updateTool also allows you to upgrade the firmware on both heliCam™ C4 and heliDriver™ D3 from the host computer using an installable board image.

If you wish to do so, make sure that the following prerequisite is met before continuing.

- You have retrieved the installable Image Package, with the extension ".ipkg", from the Heliotis webpage as described in the paragraph on *downloading Heliotis software*. There are multiple Image Packages available containing different versions of the firmware. Double-check that you have the desired version, which is usually the most recent one.

Then, update the lock-in camera in the updateTool as follows (see Fig. 2.13).

Click on the "Update Device" button, select the firmware Image Package you downloaded and press "Open". The updating process gets initiated and can be tracked in a console that opens. The message "update done" appears once the installation is complete. Please be patient as the update can take several minutes. Since a reboot is initiated automatically, you can finish the update by clicking "Close".

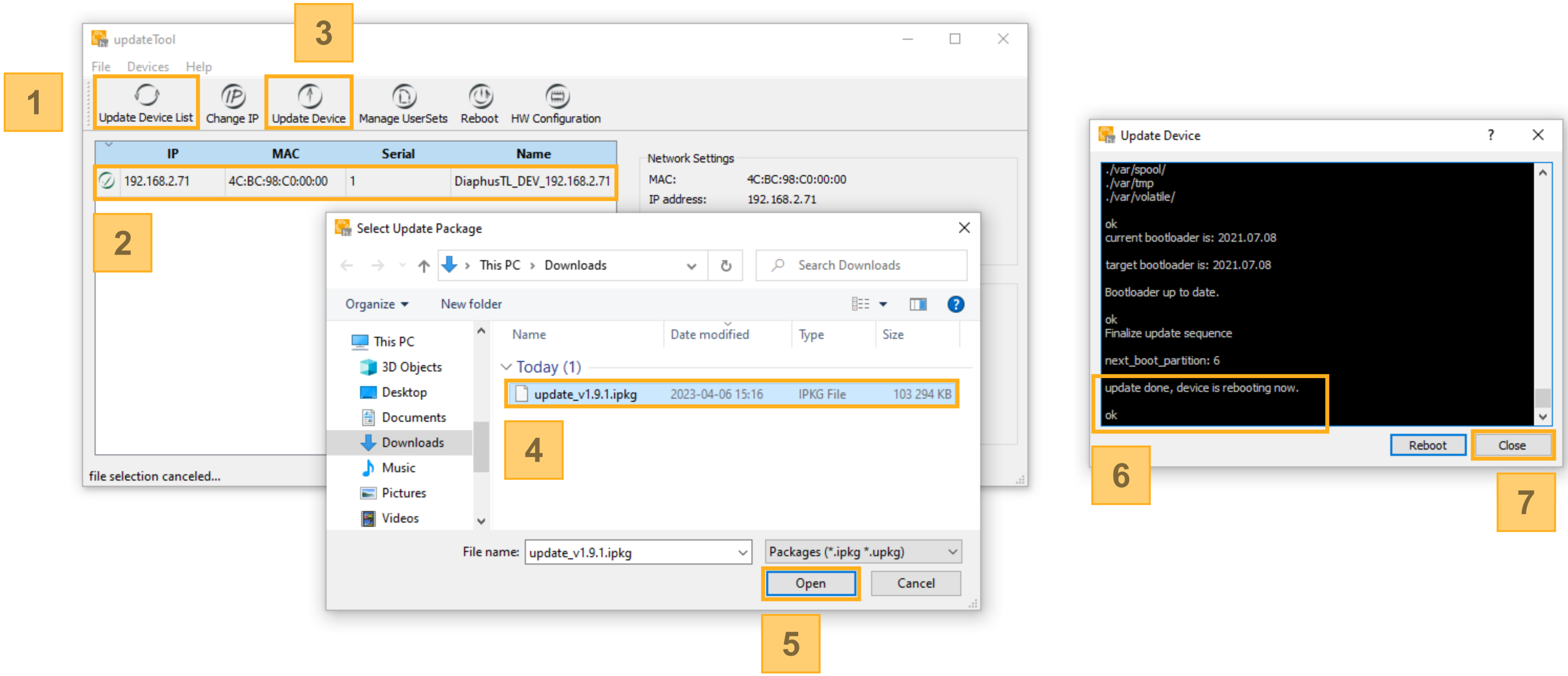


Fig. 2.13: Firmware Update

1. Update the device list.
2. Select the heliCamTM C4.
3. Click on the "Update Device" button.
4. Select the firmware Image Package you downloaded.
5. Press "Open".
6. Wait until the Message "update done" appears in the box that pops up. Please be patient. The update process can take several minutes.
7. Finish the update by clicking "Close".

Trouble Shooting

After the update is done, check that you can still connect to the heliCam^{TM} C4 in updateTool. When updating the device list by pressing the corresponding button, the heliCam^{TM} C4 must be listed and bearing a green status indicator in the update Tool. Should this not be the case, proceed as follows:

- If the heliCam^{TM} C4 is displayed, but its status indicator is not green:

  ⇒ Make sure that the version of Diaphus running on your computer matches that of the newly installed firmware as described in the previous paragraph.

  ⇒ Then, press "Reboot", wait 10-30 seconds until the reboot is complete and update the device list again. (The first boot takes longer.)

- If the previous step was unsuccessful or the heliCam^{TM} C4 is not listed in the updateTool:

  ⇒ Perform a power cycle (unplug the power supply and plug it back again) and update the list of devices after it booted.

Should the list still not contain the heliCam^{TM} C4, contact Heliotis support. Please report the LED status on the heliDriver^{TM} D3 so that Heliotis can provide you with targeted help.

CHAPTER

THREE

B) GET STARTED

The following section describes a simple starter experiment to test your setup and to get familiar with the heliCam™ C4 as well as the application software used for its control.

3.1 Outline of Starter Lock-In Measurement

The LED included in the standard shipment is used to produce a continuous, sinusoid optical signal with a well-controlled carrier frequency of ten kilohertz and constant modulation amplitude. The heliCam™ C4 can demodulate this input. We use a camera-internally generated reference signal with a slight frequency mismatch of a few ten Hertz compared to the carrier. As a result, a so-called sinusoid "beat" across the sequence of acquired frames is produced in the I and Q output components. For a detailed explanation of this phenomenon, which is mathematically related to its namesake in acoustics, the curious reader is referred to the paragraph *Idealized Signal Processing* in the next section.

3.2 Setup Preparation

To embark on the starter experiment, the hardware and software must be set up as described in the previous two chapters. Make sure that the LED Module shines through the heliCam™ C4's sensor opening onto the image sensor, as shown in Fig. 2.5.

If you wish to follow the experiment step-by-step as it is described below, you will need to have *downloaded and installed the heliViewer™* in addition to C4Utility.

3.3 Choice of Application Software

The starter experiment is readily realizable with two choices of software to operate the heliCam™ C4.

- If you wish, you can learn how to control the heliCam™ C4 in a software development environment right from the start. Scripts in different programming languages named "c4DemodSimple" implement the starter experiment.
  - When interacting with the heliCam™ C4 via the C4 Handler Library (C4Hdl) from Heliotis, these examples are found in C4Utility's dedicated C4Hdl folder (C: > Program Files > C4Utitlity > c4hdl > %os-folder% > examples).
  - If you use a third-party library to control the heliCam™ C4 through its generic camera interface directly, you find them with the general examples (C: > Program Files > C4Utitlity > examples).

    There, you may also obtain the well-documented, interactive *Jupyter Notebook* "c4DemodAdvanced.ipynb", verbally detailing the starter experiment and more advanced configuration options alongside Python code. It uses the freely available, user-friendly PyPI-package *Harvesters* to interface with the heliCam™ C4. More setup instructions are available in its "README.md" document.

- Here on the other hand, we showcase how the GUI-based application software heliViewer™ can be employed to perform basic lock-in experiments. The heliViewer™ is well-suited for such standard tasks and first-time users might do well to use it for replicating the experiment before moving on.

For a complete overview of the possible software options to interact with the heliCam™ C4, see the *previous section on integration options*.

3.4 Using heliViewer™

It is beyond the scope of this text to discuss all functionalities of heliViewer™ systematically or comprehensively. The aim here is rather that you learn about heliViewer™ 's core features in passing as you see them applied in a step-by-step user guide for making a first measurement. That said, before undertaking the lock-in measurement, there are a few purely heliViewer™-specific preparatory steps in the procedure.

3.4.1 Enable Lock-In Camera Mode

Heliotis devices other than the heliCam™ C4 can be controlled with the heliViewer™. At first use, you need to specify explicitly that you operate a heliCam™ C4 (and not the interferometers heliInspect™ H8/H9 which the heliViewer™ 's base settings support). To do so, open the heliViewer™ and set the device operation mode to “lockInCam” with the switch in toolbar. In older versions, this is achieved via the menu bar (Tools > System Settings > System) from “Default” to “LockInCam” and confirm your choice (see Fig. 3.1). The heliViewer™ layout will change to accommodate the operation of the heliCam™ C4. These settings are saved for the future.

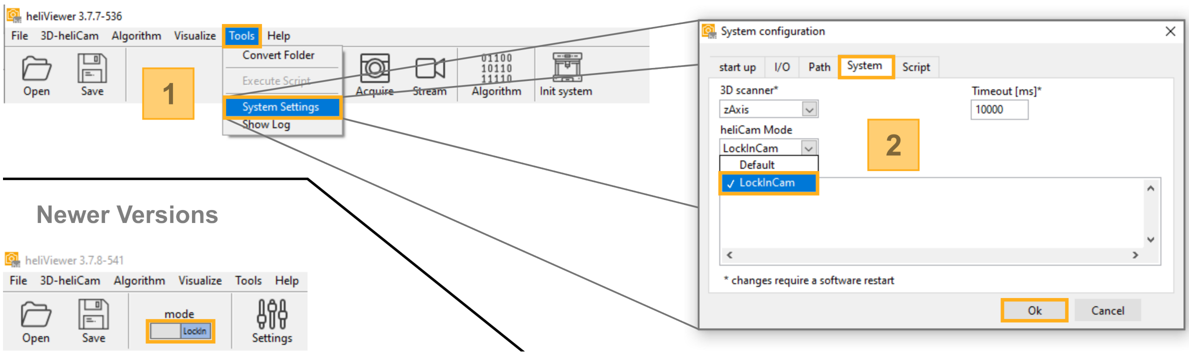


Fig. 3.1: Enabling the heliViewer™ 's Lock-In Camera Mode

3.4.2 Create Measurement Recipe

The heliViewer™ offers the possibility to save specific camera configurations as measurement “recipes”. To make the starter experiment easily reproducible, we show here how to store the corresponding operating instructions for the heliCam™ C4 in this form.

Clicking on “3D-heliCam > Manage Configuration” opens a dialog box allowing you to manage your recipes. The simplest way to create a recipe for the experiment at hand is to start from the example “C4 LockInCam_internalRef”. Ideally, you duplicate it to work with the copy as shown in Fig. 3.2.

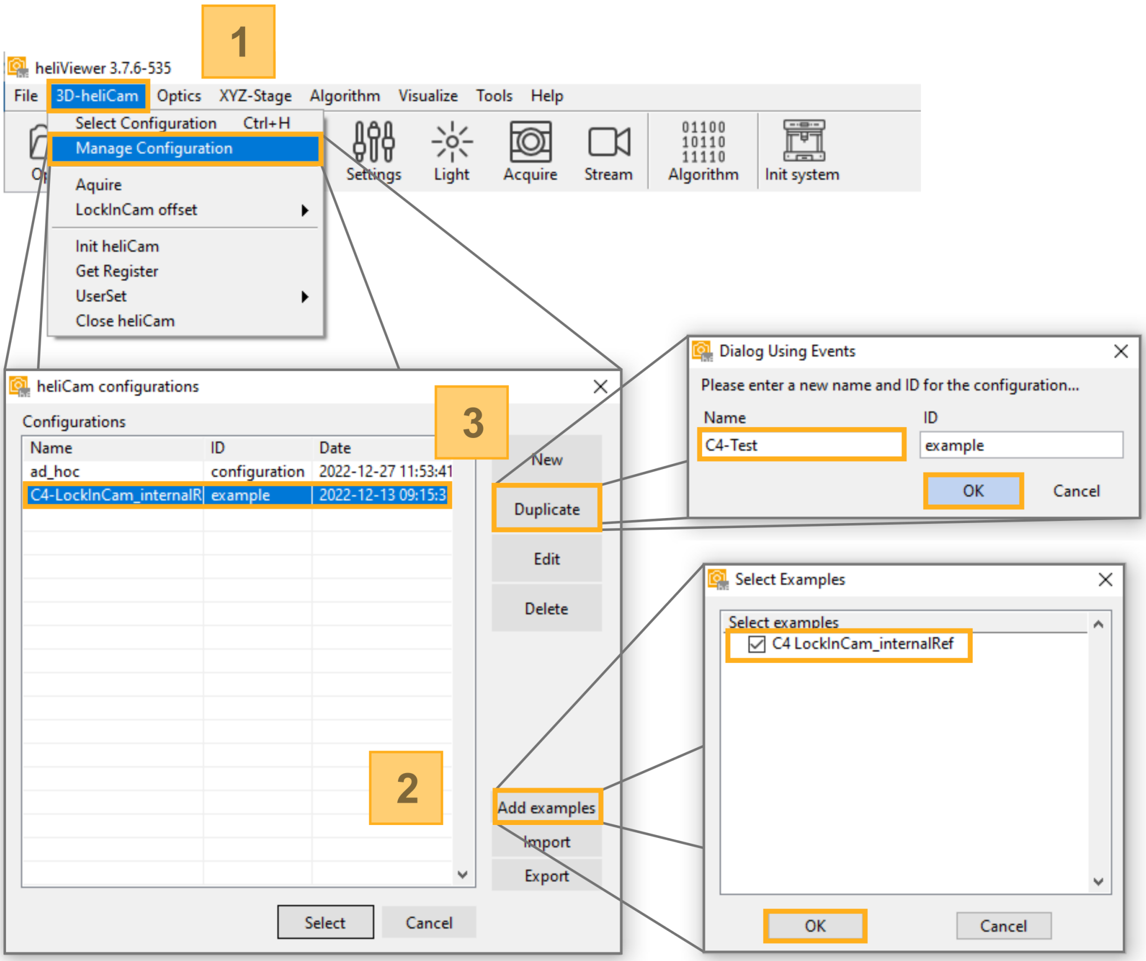


Fig. 3.2: Loading and Duplicating Heliotis Example Recipe

1. Open the configuration manager using the menu bar ("3D-heliCam > Manage Configuration").
2. Click on the "Add examples" button, select the example recipe "C4 LockInCam_internalRef" and confirm.
3. Select the new recipe, which should have appeared in the configuration manager, and press "Duplicate". Give the copy a name and press "OK".

3.5 Lock-In Camera Settings

By default, this example recipe does not yet configure all parameters according to the outlined experiment. It must be adapted slightly to introduce a small mismatch between the respective frequencies of the modulation carrier and the reference signal.

3.5.1 Lock-In Wizard

In the configuration manager, select your recipe by clicking on it. The menu to edit the recipe is then accessible via the corresponding button. (See Fig. 3.3, ditto for the following steps.) The recipe is thus shown as a list of heliCam^{TM} C4 configurations, which can be manipulated directly. It is more straightforward, however, to use the dedicated graphical user interface “Lock-In Wizard” for this purpose.

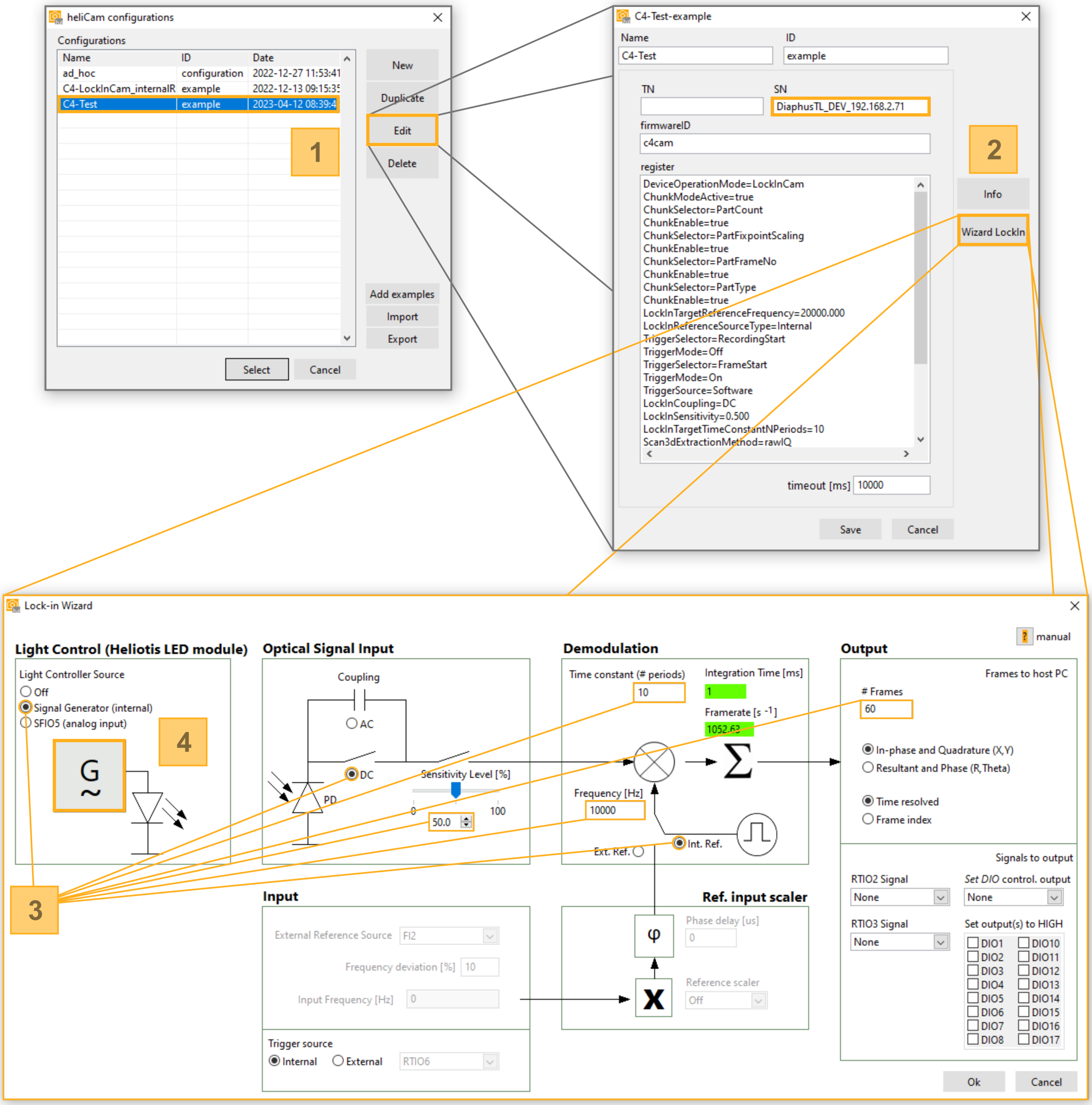


Fig. 3.3: Graphical User Interface for Configuration of Lock-In Camera

1. To alter an existing recipe, select it in the configuration manager and press “Edit”.
2. The opening window shows the list of its configuration commands. (If you changed the heliCam^{TM} ’s IP address, make sure that it matches the one in the box “SN”.) Open the “Lock-In Wizard” with the corresponding button. It allows you to change the heliCam^{TM} C4 ’s key settings interactively.
3. Where necessary, change the Lock-In Wizzard configurations according to Table 3.1. Note that the same settings are depicted in this figure except for the “Sensitivity Level”, which may differ depending on your camera version.
4. By clicking on the signal generator symbol, a separate dialog opens, enabling you to control the LED module.

Note: The "Settings" button in the toolbar gives you quick access to the same menu. In that case, however, any changes you make are saved to the to the "ad-hoc" configuration, which is also listed in the configuration manager, instead of the chosen recipe.

In the lock-in wizard's main user interface, you can configure the principal lock-in amplification parameters. A set of valid parameters is proposed in see Table 3.1. Note that the adequate the camera exposure (Sensitivity) setting changes if you have a non-standard version of the heliCam™ C4's in terms of pixel size, full well capacity, or equipment with micro lenses (see Table 1.1). In this way, one achieves an appropriate signal level and avoids saturation.

Table 3.1: Recommended Settings

Lock-In Wizzard Configurations	C4.0-S40	C4.0-S40U	C4.0-S41U	C4M.0-S4M0
Sensitivity (Level)	50 %	20 %	5 %	25 %
Coupling	DC			
Time Constant # Periods	10			
Reference Input	Internal			
Reference Frequency	10000 Hz			
# Frames	60			
Light Controller Source	Signal Generator			

Signal Generator Configurations	C4.0-S40	C4.0-S40U	C4.0-S41U	C4M.0-S4M0
Modulation Mode	On			
Frequency	9975 Hz			
Amplitude	10 %			
Offset	20 %			

The signal generator driving the test illumination can be configured in a separate window, which opens when you click on its symbol in the block diagram, see Fig. 3.4. Replicate the settings in Table 3.1 / Fig. 3.4 manually, where they deviate from the default.

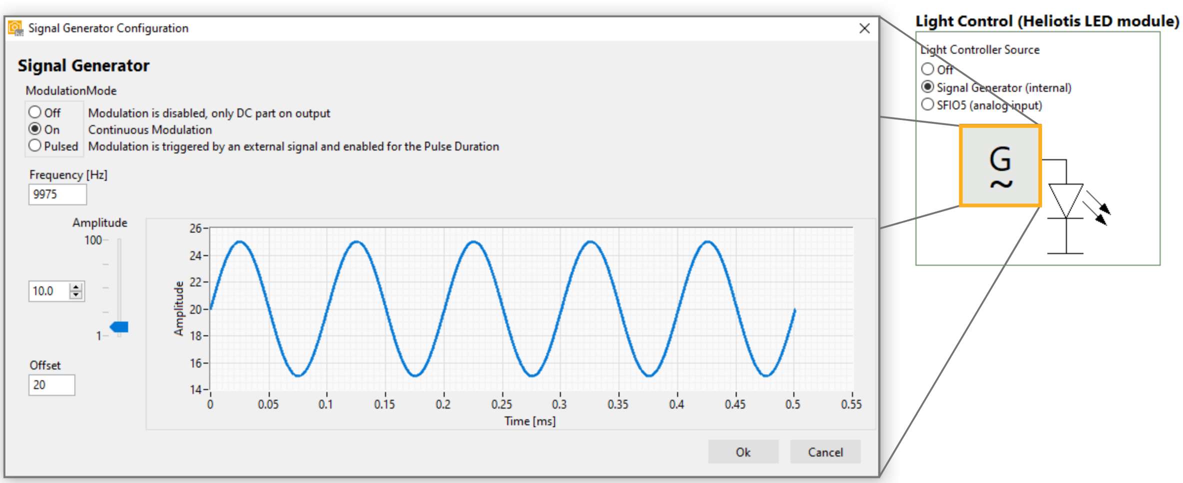


Fig. 3.4: Signal Generator Configuration

3.5.2 Key Parameters

The heliCam™ C4 is primarily a research tool. It is used in diverse experimental settings and hence supports a wide range of applications. With this focus on general applicability comes a relatively large set of configuration and control options. Navigating this landscape is not trivial, especially for first-time users. In most applications, however, you only need a small subset of what is possible.

The "Lock-in Wizard" summarizes the heliCam™ C4's most important settings. Here, we briefly walk you through them even though you might not need to alter them for the starter experiment. Concepts and parameter names generalize largely beyond the heliViewer™ to software developing environments. Configurable lock-in camera parameters and selection options are highlighted in **bold** *in the following.*

A deeper understanding of this passage requires a familiarity with the basic concepts of lock-in amplification and, at times, with the specific implementation of the principle in the heliCam™ C4. If necessary, an extensive discussion can be found in section D) Advanced Concepts and Control.

3.5.2.1 Light Control

By means of the "Light Control" field, you can configure the illumination with the Heliotis LED module. The switch **Light Controller Source** *lets you choose the source of the driving current to the LED module.*

- **Signal Generator**: *The heliDriver™ D3 comprises an signal generator, which can be configured in a separate window, see Fig. 3.4. It produces a sinusoidal modulation signal whose characteristics like* **Frequency**, **Amplitude**, *and* **Offset** *you can control.*

  Furthermore, the internal signal generator features three principal **Modulation Modes:**

  - **On**: *With this setting enabled, the signal generator produces a continuous output. This behavior is chosen in our starter experiment.*
  - **Off**: *The oscillating portion is disabled such that only a constant, non-zero* **Offset** *remains.*
  - **Pulsed:** *In the pulsed mode, the LED emits sinusoidal bursts. In between individual bursts, the illumination is constant and given by the* **Offset**. *Additional parameters govern the pulse characteristics.*
    - *The* **Pulse Duration** *of individual bursts can be set.*
    - **Trigger Source** *specifies the pin on the heliDriver™ D3's communication interface, whose signal can be used to trigger the next burst. In 'Auto' mode, the trigger is generated automatically as soon as the set* **Pulse Duration** *and* **Trigger Delay** *allow it.*
    - **Trigger Activation** *specifies the flank of the trigger signal, which is detected.*
    - **Trigger Delay** *introduces a delay of the modulation burst with respect to the trigger event, which causes it.*
    - *Triggered modulation bursts can be subjected to a common* **Phase Shift**.

  Note: Please note that you specify (peak-to-peak) **Amplitude** and **Offset** as a percentage value of the full scale. Part of the signal will therefore be cropped if,

  $$\textbf{Offset} - \frac{\textbf{Amplitude}}{2} < 0\% \quad or \quad \textbf{Offset} + \frac{\textbf{Amplitude}}{2} > 100\%$$

- **External**: *A signal from an external source is routed to the current source supply of the LED module. The default pin on the heliDriver™ D3's communication interface to feed in the electrical input (0-5 V, e.g. sine wave) is SFIO 5, cf. the heliDriver™ D3 data sheet, Section Lock-In Amplifier Module.*
- **Off**: *The driving current is disabled, the only software configuration that leaves the LED completely dark.*

3.5.2.2 Coupling

The **Coupling** *controls the activation of background subtraction. If it is set to* **AC**, *the potentially large DC component in the input is removed. Thus, the sensor's full well capacity is available for integrating the modulated, AC component, without becoming saturated by DC light. The background is not suppressed, when the mode* **DC** *coupling is enabled. The background suppression affects the signal-to-noise ratio negatively and should therefore only be used when necessary. For more detailed information see the relevant paragraph on Background Suppression*.

3.5.2.3 Sensitivity

The **Sensitivity** *(level) controls the heliCam™ C4's exposure. Roughly speaking, it determines the fraction of the measurement time during which the sensor light sensitive. A more technical explanation is given in the paragraph Processing in Pixel* et seq.

3.5.2.4 Recording Start

You may also choose the trigger, which causes the camera to start a recording. (In the heliViewer™, this can be done via "Input > Trigger Source")

- **Internal**: *A software command from the computer connected to the camera directly triggers the onset of a measurement.*
- **External**: *An electric signal (rect pulse, 0-5 V) relayed to the heliCam™ C4 via a selectable pin on the heliDriver™ D3's communication interface triggers the recording.*

3.5.2.5 Reference Signal

The synthesis of the effective reference signal from configurable parameters and (possibly) a reference input signal is technically sophisticated and complex in its details. Here, you will be shown in a simplistic way how to choose parameter values. A comprehensive and mechanistic explanation can be found in paragraph Reference Signal Synthesis of section *D) Advanced Concepts and Control*.

The **Reference Frequency** *("Input > Frequency") must be set to the frequency of the reference signal.*

The heliCam™ C4 lock-in camera can derive the pace of demodulation from an internal or an external clock. Which mode is enabled depends on the **Reference Input** *setting (configurable in lock-in wizard under "Input > Reference Input"):*

- **Internal**: *The heliCam™ C4 synthesizes an effective dual-phase, pulse wave reference signal with a reference frequency as specified by the corresponding parameter.*
- **External**: *An external reference input (rect wave, 0-5 V) is provided to the heliCam™ C4 via a pin on the heliDriver™ D3's communication interface. As a first approximation, the injected pulse wave can be considered as the in-phase portion of the reference signal with which the optical input is mixed in lock-in amplification. In the external mode, additional parameters are used to configure and modify the reference input.*
  - *The* **Reference (Trigger) Source** *selects from which pin the reference input is drawn.*
  - *The* **Reference (Frequency) Scaler** *multiplies or divides the frequency of the reference input by a select factor. Its original frequency multiplied or divided by this factor must be equal to that of the carrier of the optical input signal.*
  - *The* **Phase Delay** *parameter specifies the delay of the reference trigger input introduced on the way to the image sensor.*
  - *The maximum* **(Expected) Frequency Deviation** *makes the measurement tolerant to unsteadiness of the reference input frequency up to the specified value in percent.*

Note: Please note that the idea of considering the reference input directly as the reference signal has its limits. Attributes other than its frequency, such as amplitude, offset, and duty cycle are ignored. Also, you must specify the **Reference Frequency** parameter correctly even when you use an external reference input.

3.5.2.6 Time Constant

The **Time Constant** *defines the number of periods over which the mixed signal is integrated into a frame. Thus, it serves a double role as the filter width and the sampling period. Increasing this parameter gives you a stronger signal and makes it more selective for the target reference frequency.*

3.5.2.7 Frame Rate

A frame rate violation can occur with default settings if the following inequality is not satisfied.

$$\frac{\textbf{Time Constant} - 0.5 + int\left(\textbf{Coupling} == \textbf{AC}\right)}{\textbf{Reference Frequency} \times \left(1 + int\left(\textbf{Reference Input} == \textbf{External}\right) \times \frac{\textbf{Frequency Deviation}}{100\%}\right)} - \left(\textbf{Time Constant} - 0.5\right) \times 6.3 \times 10^{-6} s > \frac{1}{f_{lim}}$$

, where $f_{lim} = 4960\ Hz$ *in the case of the heliCam™ C4 and* $f_{lim} = 1390\ Hz$ *for the megapixel heliCam™ C4M.*

Note: If the set frame rate is too high for the lock-in camera, it does not transfer measurement data. With conventionally accessible settings, the lock-in camera is not fully optimized to achieve high frame rates. A corresponding mode will become available with future software updates.

3.6 Measurement Data

Now ready to start the measurement, click “Acquire” in the toolbar and wait a few seconds. The heliCam™ C4 should acquire a three dimensional “data volume matrix”, i.e., a sequence of frames - 60 by default. Each frame can be thought of as an image with “complex pixel values”, whose real and complex parts part represent the I and Q components resulting from dual-phase lock-in amplification, respectively. The expected result is shown in Fig. 3.5. With baseline settings, the heliViewer™ exclusively displays sections through the “raw I volume”.

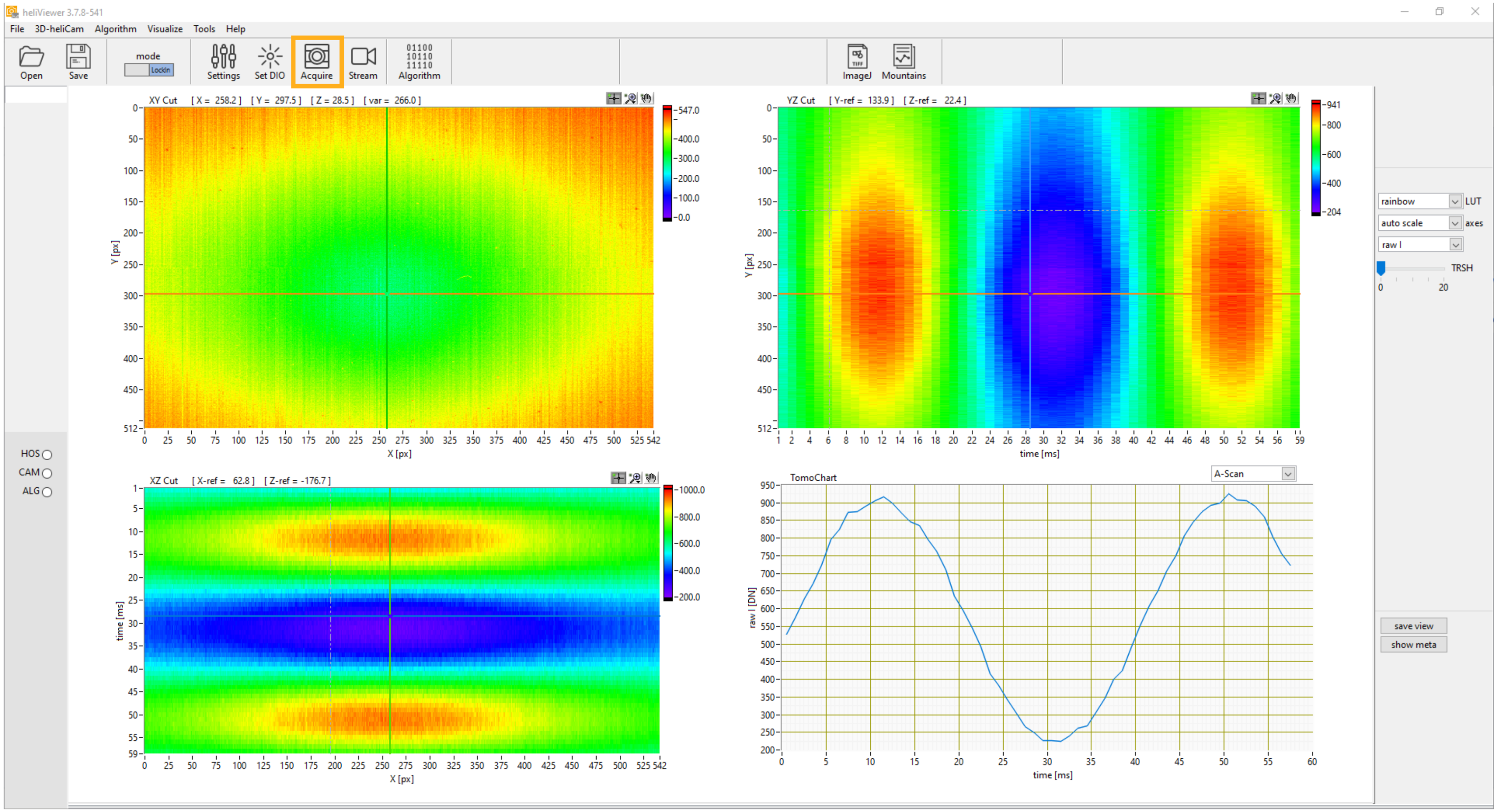


Fig. 3.5: Expected Raw I/Q Result of Starter Lock-In Measurement

After completing the heliCam™ C4 ' s configuration, press "Acquire" in the tool bar to take a measurement. HeliViewer™ will show the raw I component of your measurement. You should expect a similar result with a distinct sinusoid tendency across the series of acquired frames. The beat frequency, f_b is expected to coincide with the carrier/reference frequency mismatch, here 25 Hz. That this is so can be checked by estimating the beat period, T_b. For the data presented in this manual, we have:

$$f_b = \frac{1}{T_b} \approx \frac{1}{40\,ms} = 25\,Hz$$

3.6.1 Fixed Pattern Noise

The raw I and Q measurement data is not centered at zero. For one, these data are offset by half the full scale of possible values, i.e., FS/2 = 1024/2. Additionally, they are affected by fixed pattern noise (FPN, see Fig. 3.6 a). This type of lateral noise is due to small differences in the offset of individual pixel units across the image sensor array. The pixel-specific offset it introduces depends on camera settings like the sensitivity and environmental parameters, such as the operation temperature but is otherwise constant.

3.6.1.1 Estimating Offset from Fit

In this experiment, the I/Q components of any single pixel are known in advance to vary sinusoidally with time. Each pixel's individual offset, including the FPN component, can thus be estimated easily by fitting the expected time dependence function (see Fig. 3.6 b). In heliViewer™, this option is available by default to convert raw I/Q values to offset-free I/Q values proper by subtraction.

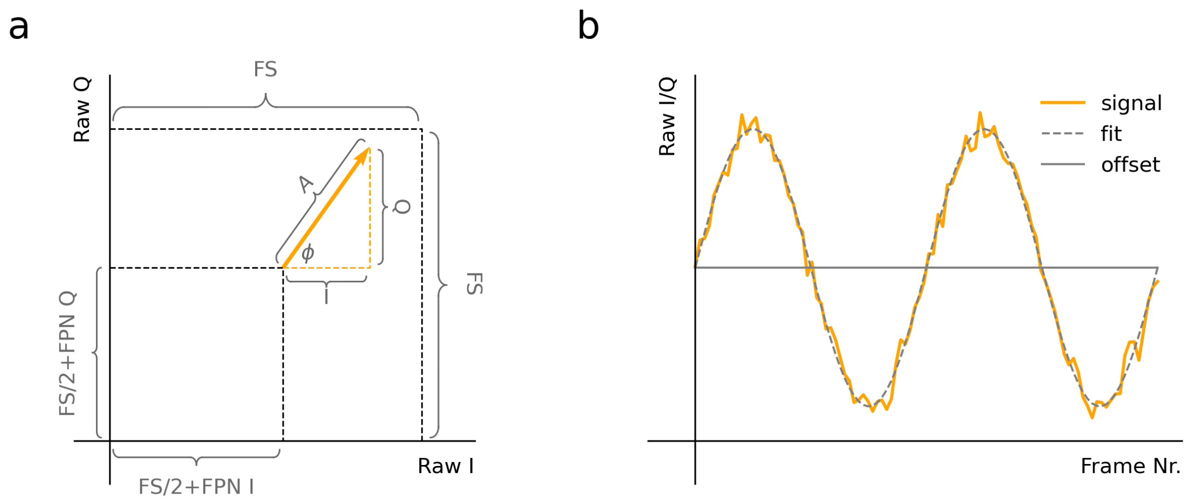


Fig. 3.6: Offset in Raw I/Q Measurement Data

a) Offset in single pixel
b) Offset removal by sinusoid fit

FS = Full Scale, FPN = Fixed Pattern Noise

3.6.1.2 Measuring Offset

More generally, the offset can be measured by illuminating the sensor with the DC part of the input alone, under the same experimental conditions otherwise.

The constant illumination component should be kept on when evaluating the offset, because said offset also depends on the total amount of incoming light the pixel is exposed to. That is because the DC attenuation factor inherent to the lock-in principle is finite and the constant part is often much larger than the time dependent one.

In the case at hand, you can set the **Modulation Mode** to "Off" (see Fig. 3.7) to disable the illumination's AC part.

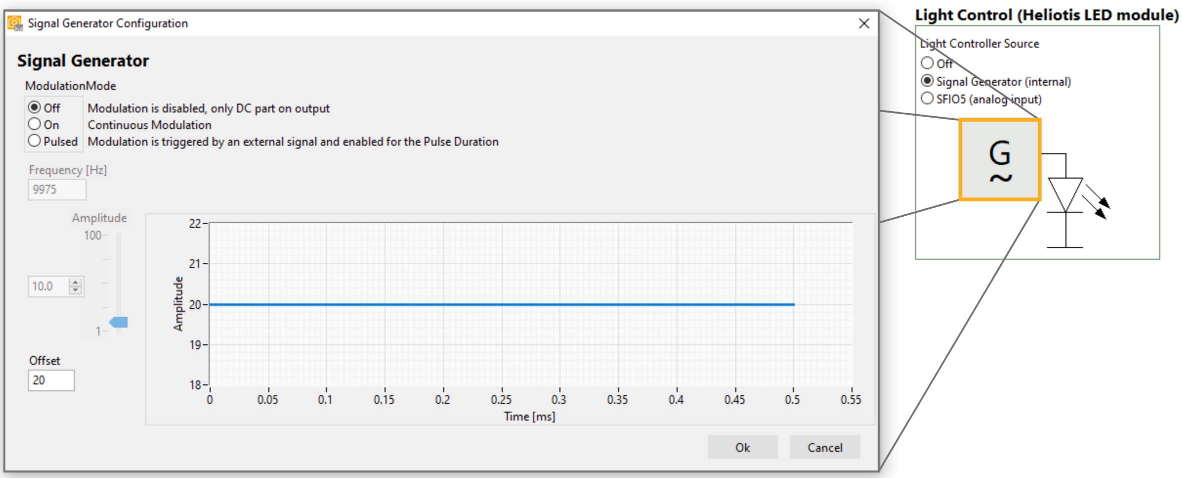


Fig. 3.7: Signal Generator Setting for Offset Measurement
To measure the offset, set the signal generator's Modulation Mode to "Off" in the lock-in wizard (Settings > Lock-In Wizard). Do not forget to turn it back on after having recorded the offset.

Trigger another acquisition afterwards. In the heliViewer^{TM}, such background data can be saved as an "offset map", according to which the offset can be removed automatically in subsequent measurements (for step-by-step instructions, see Fig. 3.8).

3.6.2 Conversion to Polar Coordinates

It is especially important to remove the offset, I_0 and Q_0, from the raw measurement results I_{raw} and Q_{raw} before you convert to polar coordinates (see heliViewer^{TM} example in Fig. 3.9), so that you obtain correct values for amplitude A and phase φ.

$$A = \sqrt{I^2 + Q^2}$$

$$\varphi = arctan2(Q, I)$$

, where $I = I_{raw} - I_0$ and $Q = Q_{raw} - Q_0$.

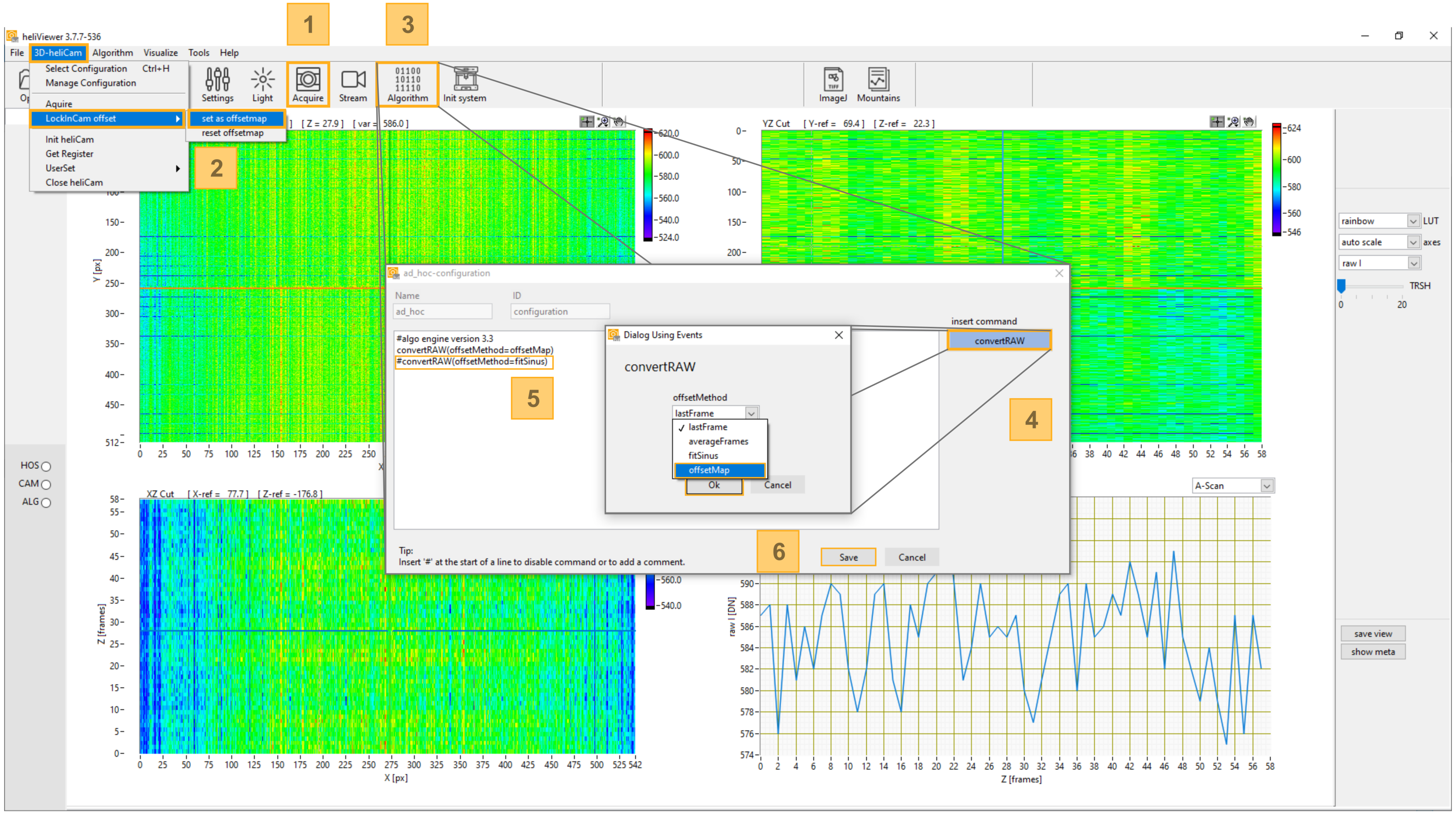


Fig. 3.8: Offset Measurement and Subtraction

1) After setting the carrier amplitude to zero, make a measurement of the offset.
2) Set the recorded data as “offset map”.
3) Open the “Algorithm” dialogue box.
4) Add a new algorithm command that uses the offset map to convert raw data.
5) Remove/comment the default conversion method based on a sinusoid fit function.
6) Confirm your changes.

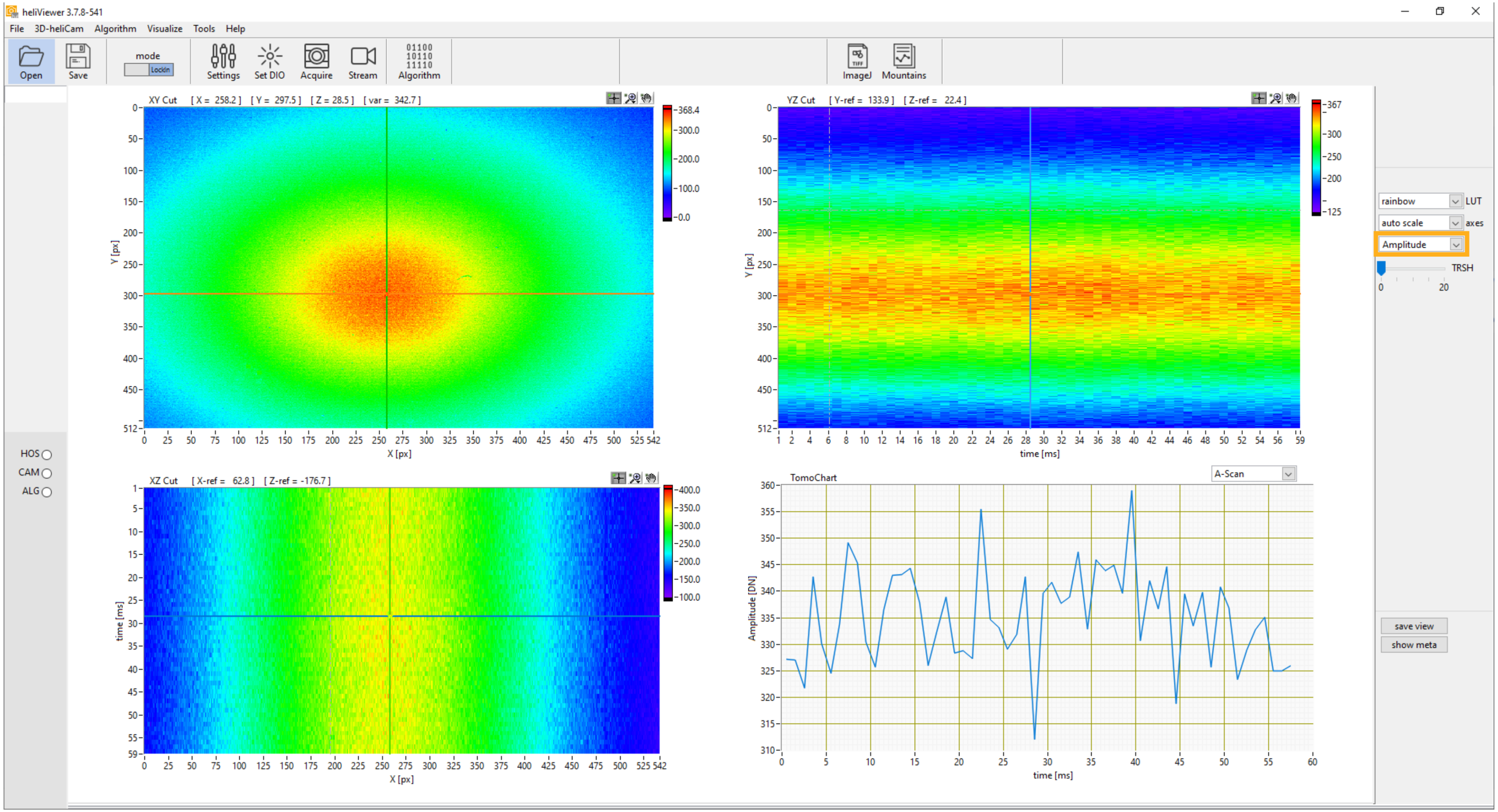


Fig. 3.9: Expected Amplitude Result of Starter Lock-In Measurement

The conversion to polar coordinates, either with offsets from the default sine fit or a set offset map, is seamless in the heliViewer™. Simply choose in which form you wish to display the results on the right-hand side of the heliViewer™. You may also show phase or offset-corrected I/Q values via the same menu.

Trouble Shooting

We encourage you to get in touch with Heliotis support without hesitation in case you face difficulties with the starter experiment. Error analysis is difficult without further clues, however. Here are a few hints for collecting indications about the source of the problem, debugging common issues, and getting effective help.

No Data Received:

- *Power Cycle*: If you do not get any data after launching an acquisition, switch the power supply to the heliCam™ C4 off and on again and proceed by *Checking the Software Setup* as described previously before you try once more.
- *Enabling heliViewer™ Log*: The heliViewer™ can display a log with status messages (see Fig. 3.10). They can often point you to the source of the issue. Please include a copy of the heliViewer™ log when you work with the heliViewer™ and contact Heliotis for support.

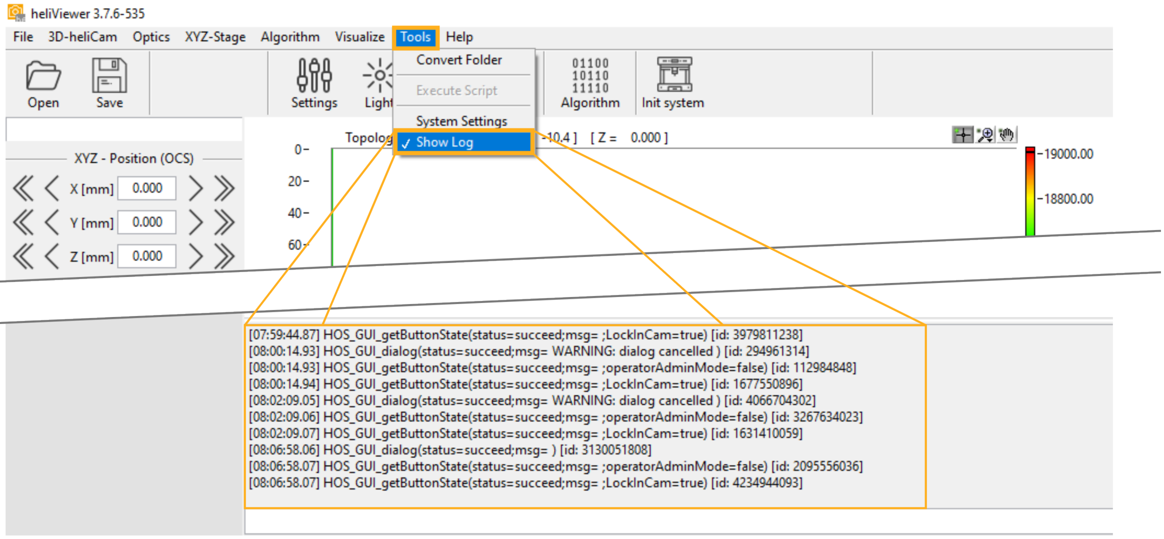


Fig. 3.10: heliViewer™ Log

Deviating Results:

- *Potential Causes*: Various issues can make your starter experiment results differ from the data presented in this manual.
- Example: It is common that you run into saturation issues - especially if you have an image sensor which features a signal enhancing micro-lens array. Saturation manifests itself in cropped I and Q signals when they exceed the full scale or, in severe cases with large DC input components, even flat signals (cf. *Background Suppression*).

  ⇒ Reduce the signal generator **Amplitude**, the **Sensitivity** (level) / enable the background suppression by setting the **Coupling** to **AC** in the *Lock-In Wizard*.

- *Sharing Data:* If you wish to consult the Heliotis support team with regards to your data, consider sharing them in the ".hdat" -format (heliViewer™ menu bar > file > Save Measurement) via file transfer. In this form, your heliCam™ C4 settings are saved alongside as metadata, which helps Heliotis considerably.

CHAPTER

FOUR

C) BASICS OF APPLICATION SOFTWARE DEVELOPMENT

Here, we briefly introduce the fundamental organizing principles behind software control of the heliCam™ C4.

These concepts and the associated terminology are heavily shaped by the Generic Interface for Cameras (GenICam) framework, to which the heliCam™ C4's programming interface complies. Rather than explaining this standard in depth, the following section wants to present you with the fundamental notions required to adapt Heliotis provided example code in C4Utility according to your needs. For more complete information, the reader is referred to the Programmer's Guide of the heliInspect™ H8 interferometer, whose software integration works on the same principles as that of the heliCam™ C4.

Implementation details differ depending on the *software integration option* you choose. Specific versions of the Programmer's Guide of the heliInspect™ H8 and code examples for different programming languages are available. To avoid a purely abstract discussion, we give examples in Python syntax in the style of a camera interaction through the "Harvesters" package. Thus, the code is directly comparable with the lock-in camera specific usage examples "c4DemodSimple.py" and "c4DemodAdvanced.ipynb" (C: > Program Files > C4Utility > examples).

4.1 Feature

The heliCam™ C4's application user interface (API) defines special software variables used for reading and writing operation modes and lock-in camera parameters. They are referred to as *features*. In the starter experiment, you have already encountered some, such as the `SignalGeneratorAmplitude` or the `LockInTargetReferenceFrequency`, albeit they were plainly called **Amplitude** and **Offset**.

4.1.1 API Description

If C4Utility is installed, you can find a complete list of all currently available lock-in camera features and their properties (C: > Program Files > C4Utility > doc). Table 4.1 illustrates how features are described using the example of the feature `LockInSensitivity`.

Table 4.1: Example Feature Description

Name	LockInSensitivity
Type	Float
Visibility	Expert
OperationMode	LockInCam
AccessMode	RW
Min	0.0
Max	1.0

Specifies the sensitivity range of 0.0 – 1.0.

The highest sensitivity setting 1.0 maximizes the signal amplitude.

LockInSensitivity is an alias of the feature ExposureRatio.

This example also reveals some generic elements of features and their description.

- Features are typed like other programming variables (see Table 4.2).

Table 4.2: Data Types of Features

Data Type	Description
Boolean	Boolean value (True or False)
Command	Executable command
Enumeration	Discrete value list
Float	Floating point number
Integer	Integer number
String	Character string

- Visibility is a GenICam concept. Useful for application software developers, it specifies at what approximate level of expertise camera users should be exposed a certain feature, given its complexity, see Table 4.3.

Table 4.3: Visibility Levels of Features

Visibility	Description
Beginner	Feature can be used easily.
Expert	Feature requires in-depth knowledge of the device or transport technology.
Guru	Features requires exact knowledge about that specific device or transport technology.

- The description moreover reveals if one has the authorization to access and modify a feature (see Table 4.4).

Table 4.4: Accessibility Levels of Features

Accessibility	Abbreviation	Description
Read Only	RO	Status information only or currently not write-able because of the device state
Write Only	WO	Written feature (command)
Read and Write	RW	Full access (writing changes state or an attribute of the device)
Not Available	NA	Temporary not available
Not Implemented	NI	Not implemented on this device or not active

- Operating the device in a different mode can change the accessibility of a feature. The camera device type can be changed by the feature `DeviceOperationMode`.

Important: The heliCam™ C4 shares the same configuration interface with other Heliotis devices.

⇒ Always use the heliCam™ C4 specific setting `DeviceOperationMode = 'LockInCam'`.

- The scope of valid entries is also indicated, and a short text portrays the feature in words.

4.1.2 Access

Which features are available and how they need to be configured is the same in all development environments which are supported. The syntax to access the features varies among the different languages available, however, and is shown in sample scripts (C: > Program Files > C4Utility > examples).

With the Python library "Harvesters", you configure the heliCam™ C4 by interacting with a camera object, which is simply called camera in the examples. A feature's value is accessed by prepending `camera.remote_device.node_map.` to the feature name and appending `.value`.

4.1.2.1 Writing

Setting the `LockInSensitivity` feature to its maximum 1.0 can thus be achieved with the following line.

```
camera.remote_device.node_map.LockInSensitivity.value = 1.0
```

4.1.2.2 Reading

Similarly, reading back the camera configuration for the same parameter (and storing it in a float variable called `sensitivity`) is done as follows.

```
sensitivity = camera.remote_device.node_map.LockInSensitivity.value
```

4.1.3 Special Feature Types

Some special features are not as directly accessible as the previous example `LockInSensitivity`.

4.1.3.1 Selector

One such feature category is under the control of specific integer and enumeration features called selectors. These selectors enable indexed access to other features. What this means is best illustrated with an example.

The feature `TriggerSelector` determines which of multiple triggers (e.g, `'FrameStart'`, `'RecordingStart'`, or `'Reference'` – see Table 4.5) is configured. Features under the control of this selector, such as `TriggerSource`, change their behavior according to the value of the selector. `TriggerSource`, for instance, controls which input channel is used for the selected trigger. To choose the input pin `'FI2'` for the `'Recording Start'` trigger, for instance, one would write:

```
camera.remote_device.node_map.TriggerSelector.value = 'RecordingStart'
camera.remote_device.node_map.TriggerSource.value = 'FI2'
```

In the feature description document, the selector features include a list with all possible selection options. Selector-controlled features have the corresponding selector printed in square brackets after their name.

Table 4.5: Selector and Selector-Controlled Features

Selector	
Name	TriggerSelector
Type	Enumeration
Visibility	Beginner
AccessMode	RW
EnumEntry	• AcquisitionStart • FrameStart • FrameBurstStart • RecordingStart • Reference

Selector-Controlled	
Name	TriggerSource [TriggerSelector]
Type	Enumeration
Visibility	Beginner
AccessMode	RW
EnumEntry	• Software • Auto • ... • FI2 • ...

4.1.3.2 Target and Actual

There are lock-in camera parameters which can only assume discrete values in their range of validity. The `LockInReferenceFrequency` feature, for example, can only take values that are a fraction of the sensor's clock frequency. In this case, the parameter is covered by two separate features (see Table 4.6). The user sets a "target" feature, from which the closest possible parameter value is deduced automatically and stored in the feature reflecting the "actual" setting. The actual value cannot be written directly but is readable.

Table 4.6: Target and Actual Feature Pairs

Target	
Name	LockInTargetReference-Frequency
Type	Float
Visibility	Beginner
OperationMode	LockInCam
AccessMode	RW
Min	305 Hz
Max	135000 Hz

Actual	
Name	LockInActualReference-Frequency
Type	FloatReg
Visibility	Beginner
OperationMode	LockInCam
AccessMode	RO

4.2 Status, Trigger and Event

The camera goes through a sequence of states during a measurement (see Fig. 4.1), more than one of which can be active at the same time. Changes of state require an internal – often software-controlled – or an external trigger signal (cf. *paragraph on the temporal sequence of the sensor operation*). Following a change of state, software events may be sent or recorded.

4.2.1 Monitoring and Control of Measurement Sequence

Let us consider the initiation of a measurement to illustrate what this means in practice.

1. During acquisition, the heliCam™ C4 is initially in a state where it waits for the `'FrameStart'` trigger, the first signal required to start a measurement.
2. Upon arrival of this trigger, the lock-in camera enters another state in which it waits for the `'RecordingStart'` trigger.
3. Only when it receives this second trigger, does it get into a third state, one of active recording.

Note: There is currently no option to acquire individual frames. In each measurement, an entire burst of frames is recorded. Note that both the `'FrameStart'` and the `'RecordingStart'` trigger, are thus only needed once per measurement to induce its beginning.

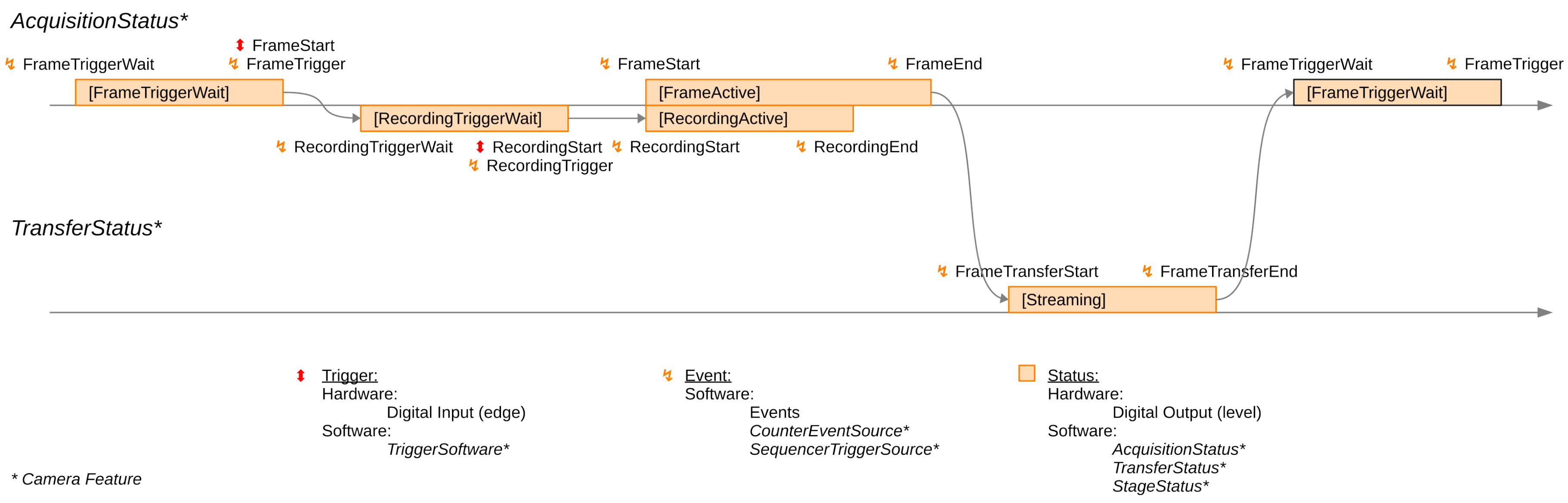


Fig. 4.1: Status and Event Signaling during Measurement Sequence

4.2.1.1 Trigger Configuration

As you have seen in a previous example, these triggers are configured via selector features. For further illustration, let us assume more specifically that we wish to start a new measurement with a software command, `camera.remote_device.node_map.TriggerSoftware.execute()`. In this case, we specify that the `'FrameStart'` trigger should come internally from `'Software'` and set the `'RecordingStart'` trigger to `'Off'`. By switching it off, `'RecordingStart'` is triggered automatically after a “FrameTrigger” event.

These settings can be achieved with the following code sniplet.

```
camera.remote_device.node_map.TriggerSelector.value = 'FrameStart'
camera.remote_device.node_map.TriggerMode.value = 'On'
camera.remote_device.node_map.TriggerSource.value = 'Software'

camera.remote_device.node_map.TriggerSelector.value = 'RecordingStart'
camera.remote_device.node_map.TriggerMode.value = 'Off'
```

Note: The `'RecordingStart'` trigger goes directly to the image sensor. To start a measurement with an external synchronization signal via the heliDriver™ D3's communication interface, you thus usually employ this trigger. To do so, enable it and set the `TriggerSource` feature to the relevant input pin. Note also that the `'FrameStart'` signal cannot come from an external source.

4.2.1.2 Status Output

You may also wish to monitor the status of your camera with an oscilloscope. To route a status signal, such as `'RecordingActive'`, in real time to a heliDriver™ D3 output pin, e.g., `'RTIO2'`, you may use the selector `LineSelecter` and the feature `LineSource` depending on it.

```
camera.remote_device.node_map.LineSelector.value = 'RTIO2'
camera.remote_device.node_map.LineSource.value = 'RecordingActive'
```

For currently available status, trigger and event monitoring/control, see chapters 1, 6, and 8 of the device feature description document (C: > ProgramFiles > C4Utility > doc > ftrDesc.pdf). **Status signals from the camera are delayed by ~ 1 µs.**

4.3 Retrieving Measurement Data

After a measurement, we would like to retrieve the data. This is not done via heliCam™ C4 features. Measurement data are transferred as multi-part buffers. Consult the code examples (C: > ProgramFiles > C4Utility > example > Python) to learn how they are retrieved.

4.4 Basic Sequence of Operations

Application programs to operate the heliCam™ C4 should follow the sequence shown below. When developing camera software, we recommend you start with a Heliotis code example and adapt it while preserving the following structure.

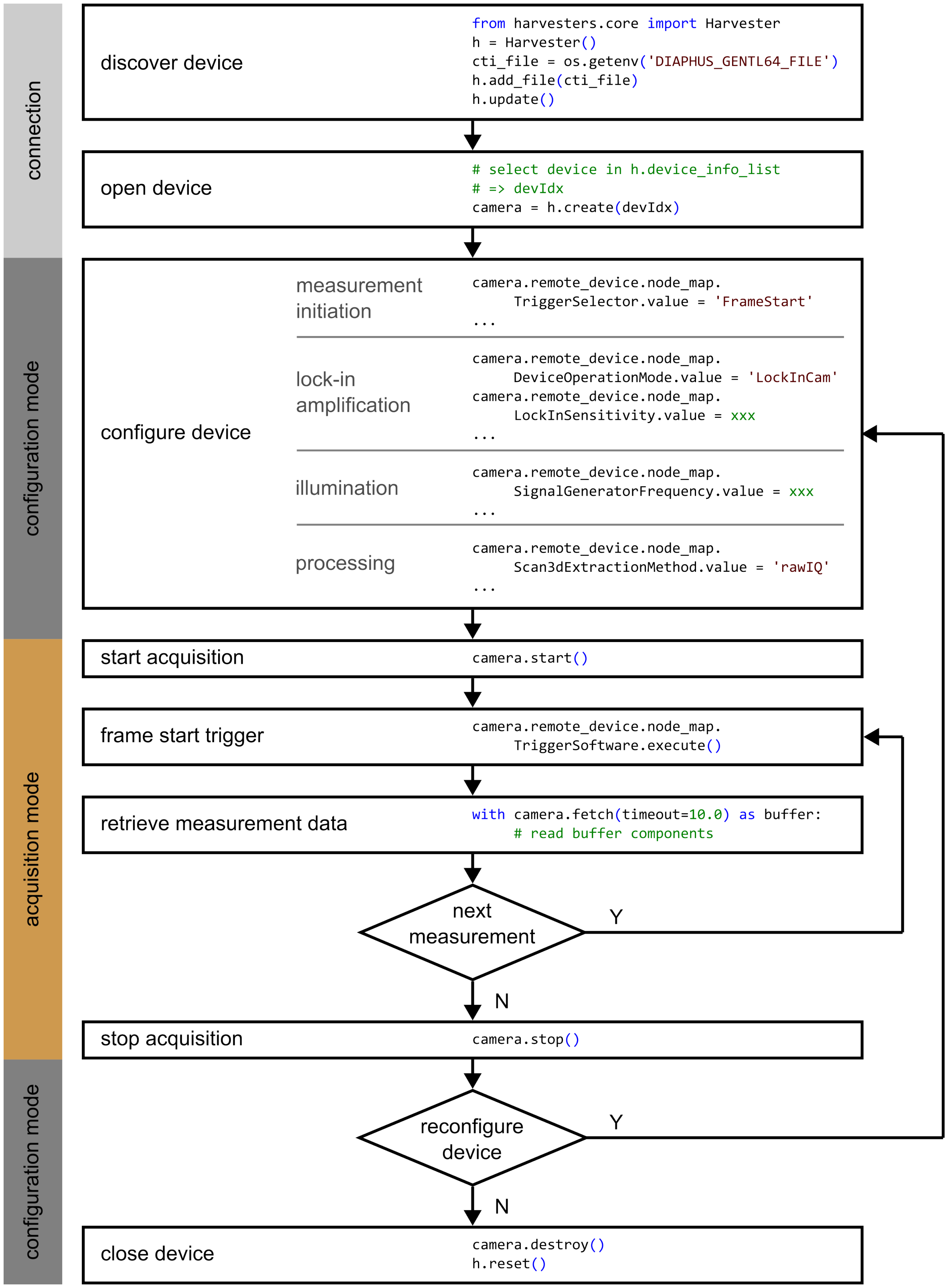


Fig. 4.2: Basic Sequence of Operations

Note: Only in "configuration mode" can the heliCam™ C4's settings be altered. Once the acquisition has started, this is no longer possible until it is stopped again.

CHAPTER

FIVE

D) ADVANCED CONCEPTS AND CONTROL

This chapter offers a detailed, mathematical, and mechanistic view of the measured signal, which enables the user to exploit the full potential of the heliCam™ C4 lock-in camera.

5.1 Lock-In Amplification

This first section aims to convey the basic theory behind lock-in amplification in depth to users with a technical background, who are not fully familiar with the subject. Later sections draw heavily on the picture presented here.

A lock-in amplifier exclusively extracts frequency components in a defined band around a tunable reference frequency from the input. Lock-in amplifiers can be used to isolate the information-bearing modulation amplitude from a known carrier wave in a process called demodulation. Due to their selectivity for specific frequencies, lock-in detectors are effective at suppressing background noise.

The implementation of lock-in amplification comprises two key steps:

- First, the input signal is compared to a standard oscillation called reference signal by multiplication. This process is also called heterodyning - or homodyning if the reference oscillation has the same frequency as the input.
- Then, the result is averaged in time.

Lock-in amplification is equivalently described in the frequency domain as (down-)mixing and subsequent low-pass filtering.

5.1.1 Single- and Dual-Phase

In their most basic form, so-called *single-phase* lock-in amplifiers also attenuate signal components that are out of phase with the reference signal even if they oscillate at the same frequency. *Dual-phase* or *phase-sensitive* lock-in amplification refers to a more advanced technique, which can detect both the amplitude of the input oscillation and its phase shift with respect to the reference signal. With this approach, used by the heliCam™ C4, the lock-in process is repeated once more with the reference signal shifted by $\frac{\pi}{2}$ (see Fig. 5.1).

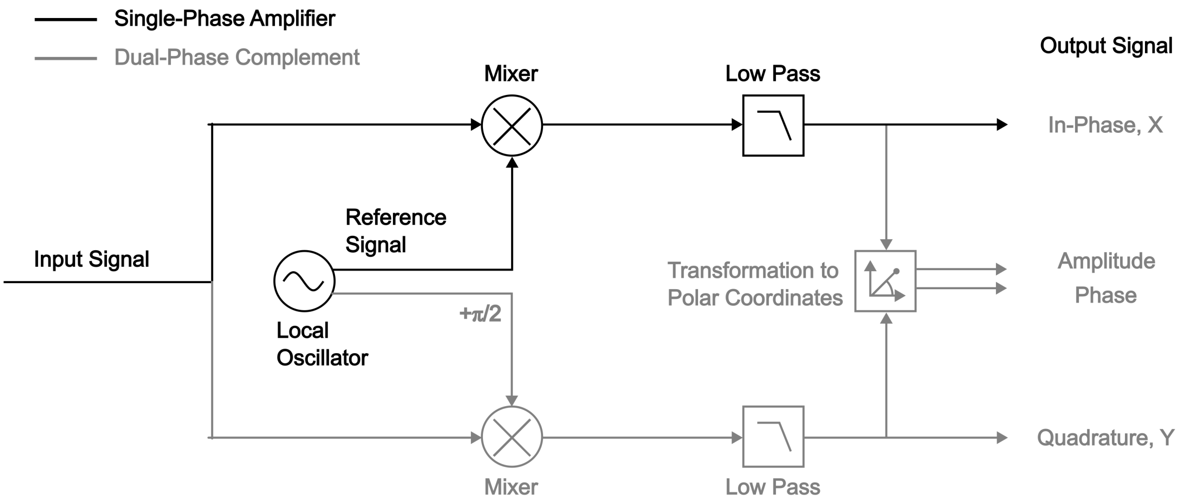


Fig. 5.1: Block Diagram of Single- and Dual-phase Lock-In Amplification
Lock-in amplification selectively extracts frequency components around the reference frequency. To this end, the input is mixed with a reference signal provided by a local oscillator and subsequently low-pass filtered. Single-phase lock-in amplification (black part) not only suppresses signal components with frequency- but also with phase-mismatch relative to the reference signal. With a dual-phase lock-in design (grey part included), the amplification is repeated with a $\frac{\pi}{2}$-shifted copy of the reference signal. The two outputs components, “In-Phase” and “Quadrature” after their phase relation to the reference, are usually transformed to polar coordinates. In this manner, both the signal amplitude of the passing frequency components and their phase with respect to the local oscillator can be retrieved. In the literature on lock-in amplification, “In-Phase” and “Quadrature” components are often referred to as X and Y, respectively.

Most lock-in amplifiers use a sine wave as reference signal. It is a pulse wave in some instruments, however, including the heliCam™ C4. These lock-in amplifiers are also sensitive to odd harmonics of the fundamental reference frequency. For the sake of simplicity, we will first focus on ideal dual-phase demodulation with a perfect sine and its $\frac{\pi}{2}$-shifted twin, a cosine wave, as reference signals. Only then will we consider the impact of demodulating with a pulse wave instead in the next section.

5.1.2 Idealized Signal Processing

A mathematical examination of lock-in amplification reveals how the processing steps outlined above act upon the input. We will set out in time domain to track the treatment of the signal directly as it is implemented by the hardware. The analysis of the lock-in principle in the frequency domain offers a complementary view. Although very intuitive, this second perspective requires the reader to be familiar with the Fourier transform.

5.1.2.1 Time Domain

In time domain, signals are expressed by their value as a function of time. Not with all inputs is lock-in amplification easily described using this representation.

5.1.2.1.1 Sinusoid Input

Oscillatory inputs with a single frequency arise often, are suitable for analysis in time domain and the results generalize readily. They can also be considered as pure carriers, i.e., amplitude modulated signals of the simplest form, which do not contain any information. Let us initially assume a sinusoid input signal s_{in} with constant amplitude, A_{in}, frequency, f_{in}, and phase, φ_{in}.

$$s_{in}(t) = A_{in} \cdot cos\left(2\pi f_{in} t + \varphi_{in}\right) \tag{5.1}$$

Dual-phase lock-in amplification of this input, as described formally below, is graphically summarized in Fig. 5.2 at the end of the paragraph. Using complex numbers, this process can be expressed concisely. Euler's formula (5.2) establishes a relationship between the trigonometric functions and the complex exponential function.

$$e^{ix} = \cos(x) + i\sin(x) \tag{5.2}$$

From (5.2) follows that the cosine can be written as a sum of complex exponentials.

$$cos(x) = \frac{e^{ix} + e^{-ix}}{2} \tag{5.3}$$

Using this identity (5.2), the input signal (5.1) can be recast in complex form a clockwise and a counterclockwise rotating component in the complex plane.

$$s_{in}(t) = A_{in} \frac{e^{i(2\pi f_{in} t + \varphi_{in})} + e^{-i(2\pi f_{in} t + \varphi_{in})}}{2} \tag{5.4}$$

5.1.2.1.2 Comparison to Reference Signal

Writing the input in this fashion, the two-stage processing of the input in dual-phase demodulation can be mathematically treated in a single pass with a single, yet complex, reference signal $s_{ref}(t)$. The real part of s_{ref} is in phase with a local oscillator, that is setting the pace. Its imaginary part accounts for the second demodulation and is thus shifted by $\frac{\pi}{2}$ with respect to the real part. Here, s_{ref}'s two parts are presumed sinusoid. Euler's formula (5.2) is used once more for the second equality.

$$s_{ref}(t) = 2\cos\left(2\pi f_{ref} t\right) - i2\sin\left(2\pi f_{ref} t\right) = 2e^{-i(2\pi f_{ref} t)} \tag{5.5}$$

Mixing the input signal (5.3) with the reference signal (5.5) yields:

$$s_{mix}(t) = s_{in}(t) \cdot s_{ref}(t) = A_{in}\left(e^{i\left(2\pi(f_{in} - f_{ref})t + \varphi_{in}\right)} + e^{-i\left(2\pi(f_{in} + f_{ref})t + \varphi_{in}\right)}\right) \tag{5.6}$$

To measure the magnitude of the input signal, the frequency of the configurable reference signal, f_{ref}, is closely matched to the input's frequency f_{in}. The first step of lock-in amplification therefore results in two complex sinusoids with very different oscillation frequencies, called heterodynes.

- The higher frequency is given by the sum of the signal and the reference frequency and thus commonly referred to as the $2f$-*component*.
- The lower, so-called *baseband* frequency, is given by the difference between the two.

Only the baseband is of interest in lock-in amplification.

5.1.2.1.3 Averaging in Time

The mixed signal $s_{mix}(t)$ is then averaged over a shifting time interval to produce the lock-in output. Intuitively, computing this moving average on a sine wave that is much longer than the sine's period, reduces the oscillation amplitude. Conversely, if this "mean" is taken over a very short time compared to the sine's period, its amplitude is largely unaffected. Oscillations with higher frequencies therefore tend to be selectively more attenuated by the averaging.

The moving average is a linear filtering operation and can be mathematically expressed as a convolution. The impulse response of the averaging filter is denoted as $h_{avg}(t)$.

$$\begin{aligned} s_{out}(t) = (h_{avg} * s_{mix})(t) &= \int_{-\infty}^{+\infty} h_{avg}(\tau) s_{mix}(t-\tau) d\tau \\ = A_{in} \Bigg(e^{i\left(2\pi(f_{in}-f_{ref})t+\varphi_{in}\right)} &\int_{-\infty}^{+\infty} h_{avg}(\tau)\, e^{-i2\pi(f_{in}-f_{ref})\tau} d\tau \\ + e^{-i\left(2\pi(f_{in}+f_{ref})t+\varphi_{in}\right)} &\int_{-\infty}^{+\infty} h_{avg}(\tau)\, e^{i2\pi(f_{in}+f_{ref})\tau} d\tau \Bigg) \end{aligned} \tag{5.7}$$

You may recognize the integral terms as Fourier transforms of the filter's impulse response, i.e., its frequency response function, H_{avg}.

$$H_{avg}(f) = \int_{-\infty}^{+\infty} h_{avg}(\tau)\, e^{-i2\pi f \tau} d\tau = \mathcal{F}\{\, h_{avg}(\tau)\}(f) \tag{5.8}$$

Equation (5.7) can then be written more succinctly. The change is in notation only.

$$s_{out}(t) = A_{in} \left(e^{i\left(2\pi(f_{in}-f_{ref})t+\varphi_{in}\right)} H_{avg}(f_{in}-f_{ref}) +\, e^{-i\left(2\pi(f_{in}+f_{ref})t+\varphi_{in}\right)} H_{avg}(-f_{in}-f_{ref}) \right) \tag{5.9}$$

Expression (5.9) shows that the amplitudes of the output's two oscillating components are given by the filter's response at their respective frequencies. Note that the filter serves a dual purpose. On the one hand, it selects the frequency band around the reference frequency in which input frequencies are detected via the first term of the sum. On the other hand, it eliminates the second, fast undulating $2f$-component, product of the multiplication with the reference signal.

In practice, the heliCam™ C4 uses a rectangular filter function with adjustable size. In this introduction to lock-in amplification, however, we will use an ideal low-pass filter instead. The intuition gained in this simplified case remains largely valid in the detailed mathematical description of a more realistic signal processing model, which can be found in the following section.

The ideal "brick-wall" filter lets frequency components below a cut off, f_c, pass unaffected and removes all others completely. As is discussed in most textbooks on signals and systems, the impulse response, $h_{avg}(t)$, of such a filter is the $sinc$ function dilatated by the "averaging duration", T. The cutoff frequency is inversely related to this dilation factor, $f_c = \frac{1}{2T}$.

$$h_{avg}(t) = \frac{1}{T} sinc\left(\frac{t}{T}\right) \quad \overset{\mathcal{F}}{\rightarrow} \quad H_{avg}(f) = rect\left(\frac{f}{2f_c}\right) \tag{5.10}$$

$$\text{, where} \quad sinc(x) \equiv \frac{\sin(\pi x)}{\pi x} \quad \text{and} \quad rect(x) \equiv \begin{cases} 1 & \text{if } |x| < \frac{1}{2} \\ 0 & \text{otherwise} \end{cases}$$

Plugging the frequency response of the ideal low-pass filter, H_{avg}, into equation (5.9) yields an expression for the amplification output, $s_{out}(t)$.

$$s_{out}(t) = A_{in} \left(e^{i\left(2\pi(f_{in}-f_{ref})t+\varphi_{in}\right)} rect\left(\frac{f_{in}-f_{ref}}{2f_c}\right) +\, e^{-i\left(2\pi(f_{in}+f_{ref})t+\varphi_{in}\right)} rect\left(\frac{f_{in}+f_{ref}}{2f_c}\right) \right) \tag{5.11}$$

The interplay between the frequency of the input, f_{in}, the reference frequency, f_{ref}, and the filter's cut-off frequency parameter, f_c, determines the lock-in output.

The simplest case arises if the reference frequency, f_{ref}, matches the input frequency, f_{in}, exactly and the filter removes the fast-rotating $2f$-component.

$$s_{out}(t) = A_{in}\ e^{i\varphi_{in}} \text{ if } f_{in} = f_{ref} \text{ and } f_c < f_{in} + f_{ref} \tag{5.12}$$

This is the principal output of a dual-phase lock-in amplifier (see Fig. 5.2 a). The result is a complex constant with amplitude and phase given by the amplitude and the phase shift of the input sinusoid before lock-in amplification, respectively.

In the general case $f_{in} \neq f_{ref}$, three outcomes (see Fig. 5.2 b) can be distinguished based on the filter's cut off frequency, f_c.

I. When averaging over a long interval compared to the period of the signal's two frequency components, both slow- and fast-rotating signal terms are stripped away.

$$s_{out}(t) = 0 \text{ if } f_c < \left|f_{in} - f_{ref}\right| \tag{5.13}$$

In this incident, the sinusoid input signal is outside the frequency band around f_{ref}, which gets detected. If f_c tends to zero, all but oscillations at the reference frequency are rejected.

II. As the "averaging duration" shortens, f_c increases and at first, the slower oscillation alone is extracted from the mixed signal.

$$s_{out}(t) = A_{in}\ e^{i\left(2\pi(f_{in}-f_{ref})t+\varphi_{in}\right)} \text{ if } \left|f_{in} - f_{ref}\right| < f_c < f_{in} + f_{ref} \tag{5.14}$$

Note that the amplitude of the output oscillation is the same as that of the input sinusoid, s_{in}, which can therefore be retrieved. Its frequency, however, is given by the difference between the input frequency and the reference frequency, which is in general much lower than that of the input. This outcome is sometimes called a "beat" in analogy to the well-known phenomenon in acoustics occurring when two waves with slightly different frequencies are superimposed. Expression (5.12) is a particular instance of the more general case II.

III. If averaging occurs over too short a period, the fast-rotating term introduced by the mixing is not removed either. The output is the same as the signal before filtering.

$$s_{out}(t) = s_{mix}(t) \text{ if } f_{in} + f_{ref} < f_c \tag{5.15}$$

To sum up, the case distinction implies for practical lock-in applications in general that:

- The reference frequency, f_{ref}, should be chosen to match the input frequency, f_{in}.
- The filter time constant T, or equivalently the bandwidth, should be picked so that case II is attained.

Adjusting the filter size and hence f_c, may change the result of lock-in amplification more gradually if the input does not consist of a single sinusoid. Yet the result with a sine wave input can easily be extended to more complex input signals; as we will see next, they can be decomposed into their frequency components by Fourier analysis (see Fig. 5.2 c).

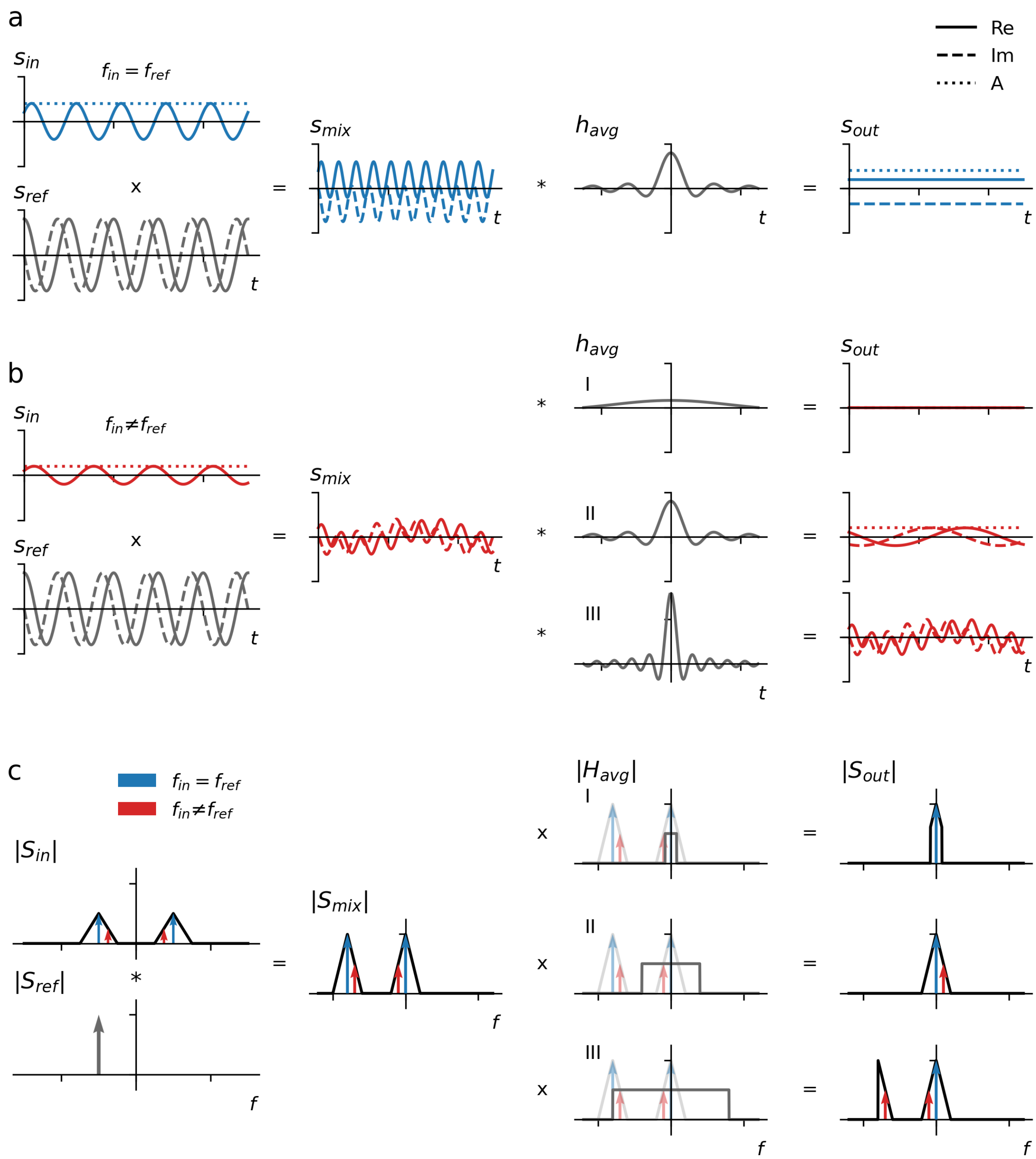


Fig. 5.2: Dual-Phase Lock-In Amplification with Monofrequent Inputs

The idealized signal processing pipeline of lock-in detection is shown sequentially from left to right. The real input signal, s_{in}, is multiplicatively mixed with a complex sinusoid reference signal, s_{ref}, which oscillates at the reference frequency f_{ref}. Subsequently, the mixed signal, s_{mix}, is averaged with an ideal low-pass filter with impulse response h_{ref}. s_{out} is complex; its real and the imaginary part, are respectively called the "in-phase", I, and "quadrature", Q, component.

a. Time domain (TD) view of lock-in detection with a sinusoid input in the special case where its frequency f_{in} is equal to f_{ref} and the filter size is adequate. The output is a complex constant whose amplitude and phase are given by the amplitude and phase shift of s_{in}. Note that $I(t) = Re\left[s_{out}(t)\right]$ and $Q(t) = Im\left[s_{out}(t)\right]$.

b. The general case of a sinusoid input when $f_{in} \neq f_{ref}$ with cases distinguished by the adjustable filter size in TD.
I f_{in} is outside the frequency band around f_{res} that passes the filter. This input is hence rejected and s_{out} is zero.
II With a shorter "averaging period", the input gets detected. The modulation frequency of sinusoid s_{out} is $f_{in} - f_{ref}$.
III If the averaging duration is too short, the undesirable high-frequency component in s_{mix} is still present in s_{out}.

c. Fourier domain (FD) view of lock-in detection with a multifrequential, amplitude modulated input. The reference frequency, f_{ref}, is equal to that of the sinusoid carrier signal, f_{car}. Frequency components treated individually in a. and b. are highlighted in blue and red, respectively. The same filters I-III as in b. are considered. Only with filter II is the modulation signal retrieved faithfully.

Conversion to Polar Coordinates

By default, the lock-in output is in cartesian coordinates. Its real and imaginary parts are named “in-phase” $I(t)$ and the “quadrature” $Q(t)$ components after their respective phase relationship with the local oscillator, that is driving the reference signal.

$$\begin{aligned} I(t) &= Re\left[s_{out}(t)\right] \\ Q(t) &= Im\left[s_{out}(t)\right] \end{aligned} \tag{5.16}$$

A conversion to polar coordinates yields amplitude and phase terms, which are often more natural to interpret.

$$\begin{aligned} A(t) &= \sqrt{I^2(t) + Q^2(t)} \\ \varphi(t) &= arctan2\left(Q(t), I(t)\right) \end{aligned} \tag{5.17}$$

5.1.2.2 Frequency Domain

Lock-in amplification is linear, meaning the system’s response to a signal is equal to the sum of the responses to its constituent parts. Signals can generally be expressed as a continuous sum of complex sinusoids with different frequencies and phases. The Fourier transform determines how strongly each of these components are present in a signal – the frequency domain representation of a signal.

$$\int_{-\infty}^{+\infty} x(t)\, e^{-i2\pi f t} dt = \mathcal{F}\left\{x(t)\right\}(f) = X(f) \tag{5.18}$$

By Fourier transforming input, intermediary and processing signals, the chain of operations in lock-in detection introduced above can be analyzed in the frequency domain. Because its action is frequency-specific by design, lock-in amplification is inherently well-describable in the frequency domain.

Fourier Transform Summary

Knowledge of a set of its notable properties facilitates the handling of the Fourier transform. It is beyond the scope of this text to justify them. Fourier properties and relations, which are used in the following are listed hereafter in table form.

Table 5.1: Properties of the Fourier Transform

Operation	$x(t)$	$X(f)$	
Linear Combination	$\alpha_1 x_1(t) + \alpha_2 x_2(t)$	$\alpha_1 X_1(f) + \alpha_2 X_2(f)$	(5.19)
Convolution	$x_1(t) * x_2(t)$	$X_1(f) \cdot X_2(f)$	(5.20)
Multiplication	$x_1(t) \cdot x_2(t)$	$X_1(f) * X_2(f)$	(5.21)
Translation	$x(t - t_0)$	$e^{-i2\pi f t_0} X(f)$	(5.22)
Modulation	$e^{i2\pi f_0 t} x(t)$	$X(f - f_0)$	(5.23)

Table 5.2: Fourier Transforms of Selected Signals

Signals with Finite Energy $x(t)$	$X(f)$		Tempered Distributions $x(t)$	$X(f)$	
$rect\left(\frac{t}{T}\right)$	$T \cdot sinc\left(T \cdot f\right)$	(5.24)	1	$\delta(f)$	(5.29)
$sinc\left(\frac{t}{T}\right)$	$T \cdot rect(T \cdot f)$	(5.25)	$\delta(t)$	1	(5.30)
$tri\left(\frac{t}{T}\right)$	$T \cdot sinc^2(T \cdot f)$	(5.26)	$e^{i2\pi f_0 t}$	$\delta\left(f - f_0\right)$	(5.31)
$sinc^2\left(\frac{t}{T}\right)$	$T \cdot tri(T \cdot f)$	(5.27)	$\cos\left(2\pi f_0 t\right)$	$\frac{\delta\left(f - f_0\right) + \delta\left(f + f_0\right)}{2}$	(5.32)
$\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}}$	$e^{-2\pi^2\sigma^2 f^2}$	(5.28)	$\sin\left(2\pi f_0 t\right)$	$\frac{\delta\left(f - f_0\right) - \delta\left(f + f_0\right)}{2i}$	(5.33)
			$\sum_{n\in\mathbb{Z}} \delta(t - nT)$	$\frac{1}{T} \sum_{k\in\mathbb{Z}} \delta\left(f - \frac{k}{T}\right)$	(5.34)

In this table, $\delta(\cdot)$ denotes the delta Dirac distribution. This generalized function, also known as unit impulse, is zero everywhere except at $t = 0$. It is furthermore constrained to satisfy the following integral relation:

$$\int_{-\infty}^{+\infty} \delta(t)\, dt = 1 \tag{5.35}$$

Shifting a function in time by t_0 can be expressed by means of a convolution with a t_0 -shifted version of $\delta(\cdot)$.

$$x\left(t - t_0\right) = x(t) * \delta\left(t - t_0\right) \tag{5.36}$$

5.1.2.2.1 Noisy, Amplitude Modulated Input

An amplitude modulated signal, s_{am}, consists of a sinusoid carrier wave, s_{car}, whose amplitude is varied or *modulated* slowly compared to its oscillation frequency (see Fig. 5.3 a). These amplitude variations bear the information contained in the signal. The time evolution of the amplitude is called the modulation signal, s_{mod}.

$$s_{am}(t) = A(t) \cdot cos\left(2\pi f_{car}t + \varphi_{car}\right) = s_{mod}(t) \cdot s_{car}(t) \tag{5.37}$$

Demodulation of such signals, with variable amplitude and thus more than a single frequency component, is a common application of lock-in amplification. It can be achieved by matching the reference frequency to the carrier frequency. Realistic inputs moreover contain background noise. So, let us examine an arbitrary amplitude modulated signal, s_{am}, with additive noise, s_σ, as input, s_{in}.

$$s_{in}(t) = s_{am}(t) + s_\sigma(t) \tag{5.38}$$

We would like to perform our analysis in the Frequency domain and must therefore find the Fourier transform of s_{in}. It is given by the sum of the Fourier transforms of s_{in}'s addends since the Fourier transform is a linear operation (5.19).

$$S_{in}(f) = S_{am}(f) + S_\sigma(f) \tag{5.39}$$

S_{am} can be stated in terms of S_{mod}, the carrier frequency, f_{car}, and phase shift, φ_{car}. Expressions (5.19), (5.21), (5.31), and (5.36) from summary on the Fourier transform are used in conjunction with the complex form of the cosine (5.3) to derive S_{am} in this form from its time domain expression (5.37).

$$\begin{aligned}
S_{am}(f) &= S_{mod}(f) * S_{car}(f) \\
&= S_{mod}(f) * \mathcal{F}\left\{\cos\left(2\pi f_{car}t + \varphi_{car}\right)\right\}(f) \\
&= S_{mod}(f) * \mathcal{F}\left\{\frac{e^{i(2\pi f_{car}t+\varphi_{car})} + e^{-i(2\pi f_{car}t+\varphi_{car})}}{2}\right\}(f) \\
&= S_{mod}(f) * \frac{e^{i\varphi_{car}}\mathcal{F}\left\{e^{i2\pi f_{car}t}\right\}(f) + e^{-i\varphi_{car}}\mathcal{F}\left\{e^{-i2\pi f_{car}t}\right\}(f)}{2} \\
&= S_{mod}(f) * \frac{e^{i\varphi_{car}}\delta\left(f - f_{car}\right) + e^{-i\varphi_{car}}\delta\left(f + f_{car}\right)}{2} \\
&= \frac{e^{i\varphi_{car}}S_{mod}\left(f - f_{car}\right) + e^{-i\varphi_{car}}S_{mod}\left(f + f_{car}\right)}{2}
\end{aligned} \tag{5.40}$$

As the last term reveals, the frequency domain description of amplitude modulation is that it produces a signal with power concentrated in two bands around plus and minus the carrier frequency.

Plugging (5.40) into (5.39) yields the frequency domain expression of the noisy, amplitude-modulated input to the lock-in amplifier.

$$S_{in}(f) = \frac{e^{i\varphi_{car}}S_{mod}\left(f - f_{car}\right) + e^{-i\varphi_{car}}S_{mod}\left(f + f_{car}\right)}{2} + S_\sigma(f) \tag{5.41}$$

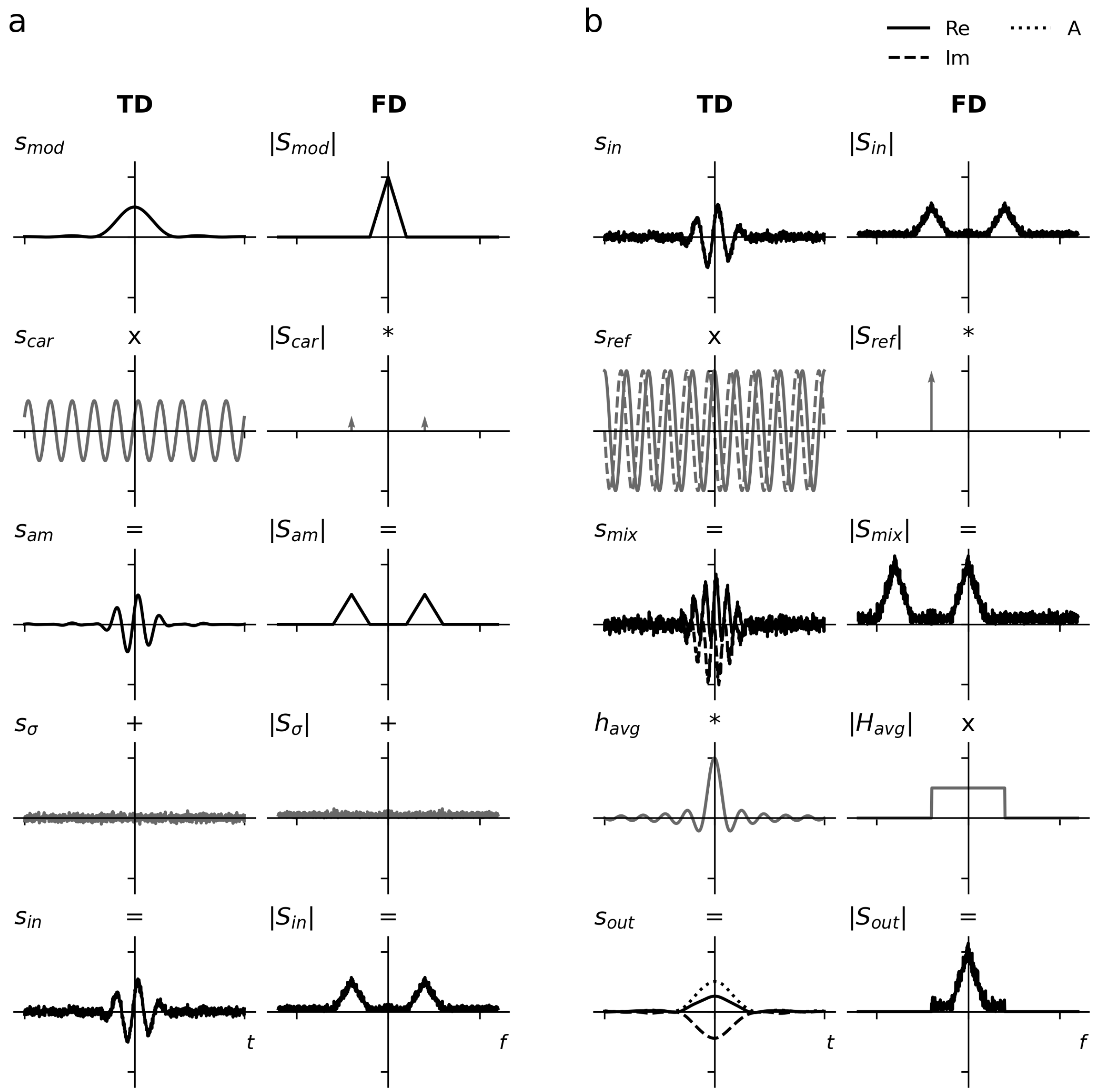


Fig. 5.3: Amplitude Modulation and Ideal Dual-Phase Demodulation with Noise
In both a. and b., time-domain (TD) signals $s_{\cdot}(t)$ are depicted alongside their frequency domain (FD) representations $S_{\cdot}(f)$.

a. Synthesis of an Amplitude Modulated Signal with Noise in TD (left) and FD (right).

   The amplitude of a sinusoid carrier signal s_{car} is varied in time according to a modulation signal s_{mod}. The result is the amplitude modulated signal, s_{am}. The FD equivalent is a convolution of the modulation spectrum, S_{mod}, with that of the carrier wave, S_{car}. The ensuing signal in FD is a duplicated and generally phase-shifted version of S_{mod} with half the original amplitude, whose two component parts are shifted to +/- the carrier frequency, f_{car}. Broadband noise, s_{σ}, is added to the signal s_{am} yielding the input signal s_{in}.

b. Dual-Phase Demodulation of Noisy, Amplitude Modulated Signal in TD (left) and FD (right).

   The noisy, amplitude modulated input signal, s_{in}, from a. is demodulated with an ideal dual-phase lock-in amplifier. First, the input, s_{in}, is multiplied with a complex sinusoid reference signal whose frequency is equal to f_{car}. With the effect in the frequency domain in mind, this step is called down-mixing. The spectrum of the product of mixing, S_{mix}, is shifted by f_{ref} with respect to that of the input S_{in}. In this fashion, one of S_{in}'s two spectral components corresponding to S_{mod} comes to lie in the baseband. S_{mix} is then low-pass filtered so that only the baseband passes. The ideal "brick-wall" filter, H_{avg}, lets frequency components below the cut off pass freely and completely blocks all others. As the noise is much more broadband than the signal, much of it gets removed along with the high-frequency copy of S_{in}. The modulation signal with little remaining noise is given by the amplitude of the complex output, s_{out}.

5.1.2.2.2 Down-Mixing

Fourier relation (5.31) spells out that the Fourier transform of $s_{ref}(t)$, given by (5.5), is a frequency-shifted Delta Dirac distribution scaled by a factor two.

$$S_{ref}(f) = 2\delta\left(f + f_{ref}\right) \tag{5.42}$$

The first step in demodulation (see Fig. 5.3 b) - multiplication of the input with the reference signal - is a convolution of the two in the frequency domain (5.21). It can be computed using (5.36). This step introduces negative shift of the frequency spectrum by f_{ref} hence the name down-mixing.

$$S_{mix}(f) = S_{in}(f) * S_{ref}(f) = S_{in}(f) * 2\delta\left(f + f_{ref}\right) = 2S_{in}\left(f + f_{ref}\right) \tag{5.43}$$

With the amplitude modulated input under consideration, S_{mix} is given by the following expression.

$$S_{mix}(f) = e^{i\varphi_{car}} S_{mod}\left(f - f_{car} + f_{ref}\right) + e^{-i\varphi_{car}} S_{mod}\left(f + f_{car} + f_{ref}\right) + \, 2\, S_{\sigma}\left(f + f_{ref}\right) \tag{5.44}$$

If the reference frequency approximately matches the carrier frequency, one part of the duplicated frequency spectrum comes to lie in the baseband. The other portion is shifted to a highly negative frequency band. If in addition $f_{ref} = f_{car}$, the baseband component of the signal coincides with the spectrum of the modulation signal up to a phase shift. (The noise is shifted in frequency too.)

5.1.2.2.3 Low-Pass Filtering

At this point, the purpose of the filtering step in lock-in amplification is straightforward. The baseband component of the signal, the first term in equation (5.44), is the only one of interest. To retrieve the modulation signal, its high-frequency copy and as much noise as possible ought to be removed by a low-pass filter.

In the frequency domain, applying a low-pass filter amounts to multiplying with its frequency response, H_{avg}. Lock-in amplification is thus captured by a simple equation, which expresses a frequency shift of the input followed multiplicative, frequency-dependent scaling of spectral components.

$$S_{out}(f) = S_{mix}(f) \times H_{avg}(f) = 2S_{in}\left(f + f_{ref}\right) \times H_{avg}(f) \tag{5.45}$$

Inserting expressions for the frequency response of the ideal low-pass filter (5.10) and S_{mix} (5.44), yields the output when used in demodulation of a noisy signal.

$$\begin{aligned} S_{out}(f) = e^{i\varphi_{car}} S_{mod}\left(f - f_{car} + f_{ref}\right) \cdot rect\left(\frac{f}{2f_c}\right) \\ + e^{-i\varphi_{car}} S_{mod}\left(f + f_{car} + f_{ref}\right) \cdot rect\left(\frac{f}{2f_c}\right) \\ + 2 \cdot S_{\sigma}\left(f + f_{ref}\right) \cdot rect\left(\frac{f}{2f_c}\right) \end{aligned} \tag{5.46}$$

Ignoring the noise term for now and assuming a finite modulation bandwidth, three cases depending on filter cut-off may be distinguished, analogous to those discussed in time-domain (see Fig. 5.2 c):

I. If the filter bandwidth is too narrow compared to the frequency spectrum of modulation signal, a non-negligible part of its power can be chucked away by the filter. A distorted version of the modulation signal is retrieved.

II. With an appropriate cut-off frequency of the ideal filter, the baseband term alone is extracted. This is the usual, desired behavior in dual-phase demodulation.

$$S_{out}(f) = e^{i\varphi_{car}} S_{mod}\left(f - f_{car} + f_{ref}\right) \tag{5.47}$$

Using the modulation property (5.23), the time-domain output can be deduced from (5.47).

$$s_{out}(t) = e^{i(2\pi(f_{car} - f_{ref})t + \varphi_{car})} s_{mod}(t) \tag{5.48}$$

The oscillatory component in (5.48) is generally of low frequency or entirely constant, as f_{ref} is usually chosen to match f_{car}. Converting the output to polar coordinates allows to retrieve the original modulation signal in the lock-in amplitude.

$$\begin{aligned} A_{out}(t) &= s_{mod}(t) \\ \varphi_{out}(t) &= 2\pi\left(f_{car}-f_{ref}\right)t + \varphi_{car} \end{aligned} \tag{5.49}$$

III. Using a filter that is too broad, high frequency components from the $2f$ spectral component may enter the output.

The frequency domain picture also illustrates nicely how noise is suppressed by the filter (see Fig. 5.3 b). Noise is usually more broadband than the modulation signal. Wherever there is no overlap with extracted modulation spectrum, it can be removed without penalty. The noise spectrum and its overlap with the signal give therefore a supplementary criterion for tuning the filter bandwidth.

5.2 Smart Pixel Image Sensor

The lock-in principle presented above is implemented directly in the heliCam™ C4's specially designed camera sensor, the proprietary heliSens™ S4. Its pixel sensor units register the light intensity in a precisely clocked, periodic fashion and promptly process acquired signals. In the following, several sensor-related concepts are introduced, which may help with the operation of the lock-in camera.

5.2.1 Temporal Sequence

We have seen that lock-in detection uses prior knowledge about the time evolution of a signal's carrier to extract only the slow-varying, information-bearing part. Thus, the exact control of the temporal sequence of processing steps is predictably crucial for the realization of this principle in a physical system.

5.2.1.1 Trigger Signals

The heliSens™ S4 relies on trigger signals to schedule its operation (Fig. 5.4 a). These control signals are tightly linked to configuration options. Understanding of how they structure the lock-in process helps exploit the full performance of the heliCam™ C4. Trigger signals can be generated camera-internally and then operate unbeknownst to the user. However, many experiments require pinpoint temporal synchronization to other elements of the set up. For these cases, the heliCam™ C4 offers the possibility to provide external trigger signals.

5.2.1.2 Period

The heliCam™ C4 initiates a measurement upon receiving a recording trigger. Thereafter, the pace is dictated by the reference trigger signal, a pulse wave which by default determines - roughly speaking - the start of a new period of the reference signal. In the heliSens™ S4, this period also imposes constraints on the filtering and sampling during analogue to digital conversion.

5.2.1.3 Frame

The optical input generally depends on the location of the pixel on the image sensor that records it. Each pixel can be interpreted to perform a multiplication of the local input, $s_{in}(t, x, y)$, with a spatially uniform, effective reference signal, $s_{ref}(t)$, followed by an integration over a selectable number of full periods, N_P. The result of this averaging is a frame (with complex pixel values due to the dual-phase nature of the lock-in implementation). Multiple frames are acquired in instant succession.

In short, a single pixel with discrete indices x and y, according to its spatial location in pixel coordinates, takes the following value in the m^{th} frame.

$$s_{out,\,m}[x, y] = \int_{t_m - \frac{T_m}{2}}^{t_m + \frac{T_m}{2}} s_{in}(t, x, y) s_{ref}(t) dt \tag{5.50}$$

Here, t_m is the timestamp at the center of the interval feeding into the frame and T_m is its duration. T_m is given by the sum of the periods making up frame m.

Lock-in amplification in the heliSens™ S4 can be brought in line with the view presented in the previous section, by expressing the output as a sequence of a mixing, a filtering, and a sampling step. To this end, the integral over a finite interval in (5.50) is restated as a convolution with a rectangular function evaluated a single point in time.

$$s_{out,\,m}[x, y] = \left(h_{avg} * \left(s_{in}(x, y) \times s_{ref}\right)\right)(t_m) \tag{5.51}$$

, where h_{avg} is the impulse response of a central moving average filter with window length T_m.

$$h_{avg}(t) = rect\left(\frac{t}{T_m}\right) \tag{5.52}$$

With an irregular reference trigger, the starts of a period are uneven. But normally, periods are of uniform duration so that the filter width is also a constant, $T = T_m \; \forall \, m$. In this case, which is presumed from here onwards, frame acquisition is regularly spaced in time with sampling period T.

5.2.1.4 Quarter Period

Again, the heliSens™ S4 performs *dual-phase* demodulation. As in the previous introduction to lock-in amplification, the notation of this twofold process is condensed using a single, yet complex reference signal, s_{ref} (see Fig. 5.4 b). Its imaginary part, accounting for the second demodulation, is also shifted by a quarter period with respect to the real part. Both these signal components are well-approximated by a pulse wave with two short, equally spaced pulses per period - every other pulse having a negative sign. s_{ref} 's fundamental frequency is the reference frequency f_{ref} (cf. Fig. 5.5).

Since by default, the external reference trigger signal is deemed to oscillate between two values *at the reference frequency*, it ordinarily signals the onset of a period. Yet to realize the effective reference signal, s_{ref}, the heliSens™ S4 needs an indication of the start of each quarter period. This timing information is extracted from the external reference trigger by a programmable processing unit for frequency scaling to a power of two. With baseline settings it performs frequency multiplication by four behind the scenes.

5.2.2 Processing in Pixel

Understanding how the camera sensor, heliSens™ S4, uses this derived quarter-period trigger to do lock-in amplification with a pulse wave as reference, demands an additional information layer.

Like other image sensors, the heliSens™ S4 is an array of light-sensitive semiconductor devices, called photodiodes, which convert the incidence of photons to an electric current. Photodiodes integrate the intensity of the light they receive in a time interval. In the heliSens™ S4, they do so over the duration of single quarter periods (see Fig. 5.4 c). The fraction of the full quarter period during which the photodiode is sensitive to light, p_s, is configurable up to a hardware overhead of $< 2\mu s$.

The signal thus retrieved in each quarter period constitutes the basic building block from which the lock-in output is synthesized by simple addition and subtraction.

$$s_{m,n,qp}[x,y] = \int_{p_s \times t_{qp_{m,n}}} s_{in}(t,x,y)dt \tag{5.53}$$

, where t_{qp} is the duration of a quarter period, identified unambiguously by indices m, n and qp.

- $m \in \{1,...,N_F\}$ specifies in which of N_F frames acquired the quarter period is situated.
- $n \in \{1,...,N_P\}$ indicates in which of the N_P periods of frame m the quarter period is situated.
- $qp \in \{I, II, II, IV\}$ specifies which quarter period in period n it is.

From this element, a complex lock-in signal per period is computed.

$$s_{m,n}[x,y] = s_{m,n,I}[x,y] + i \cdot s_{m,n,II}[x,y] - s_{m,n,III}[x,y] - i \cdot s_{m,n,IV}[x,y] \tag{5.54}$$

In each pixel, the contributions of N_P individual periods are summed up into a frame.

$$s_{out,\ m}[x,y] = \sum_{n=1}^{N_P} s_{m,n}[x,y] \tag{5.55}$$

These sums and differences of the basic element $s_{m,n,qp}[x,y]$ can be executed with low power dissipation and small footprint within the architecture of the individual smart pixel.

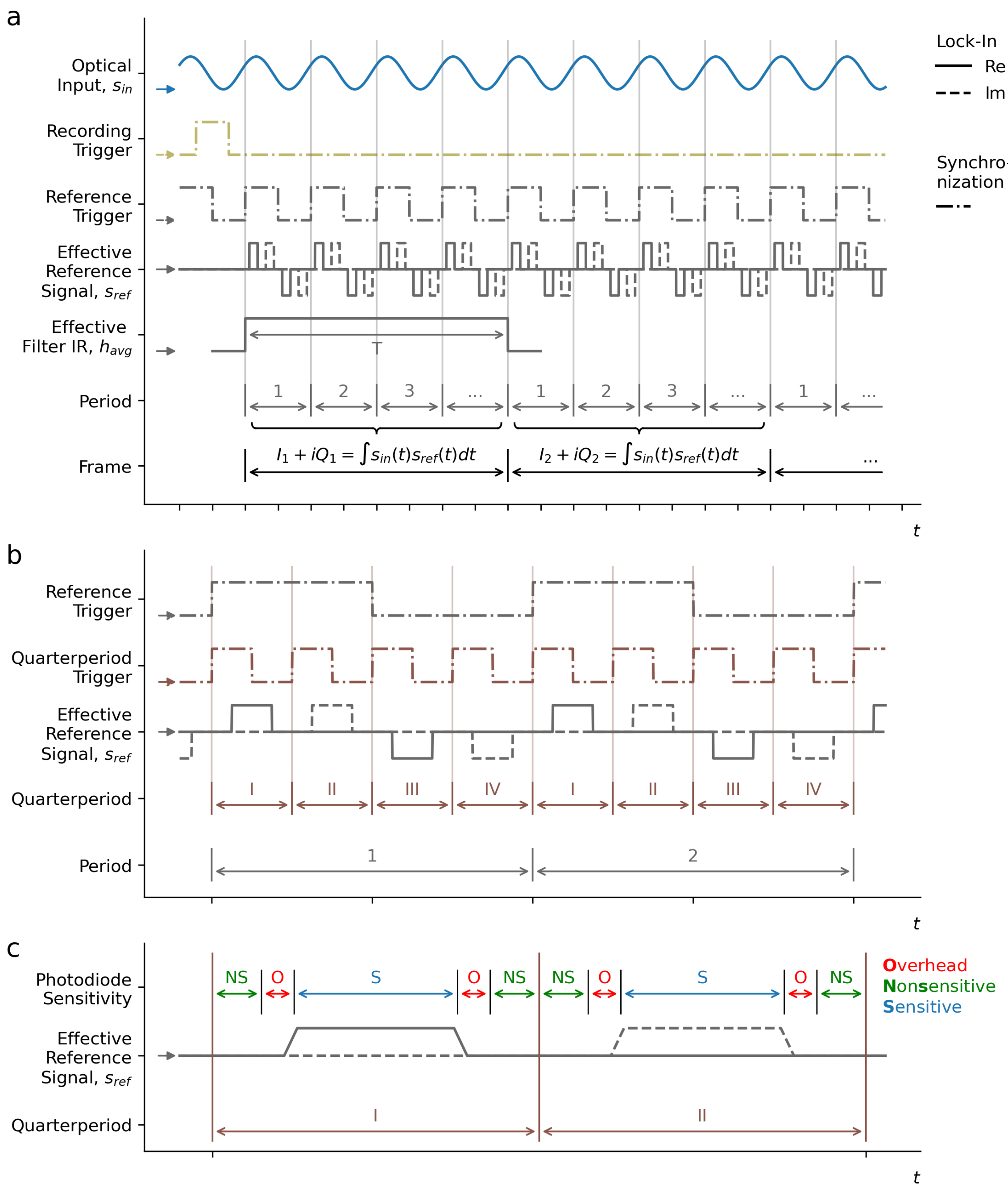


Fig. 5.4: Operational Sequence in the heliSens™ S4

a. The recording trigger prompts the start of a recording. Subsequently, the beginning of each period of the effective reference signal is prompted by the reference trigger. A frame holds a complex value for each pixel. It is the result of integrating the input mixed with the complex, effective reference signal, s_{ref}, over an adaptable number of full periods. T is both the window width of the equivalent central moving average filter, h_{avg}, and the sampling period.

b. The heliSens™ S4 needs a trigger impulse every quarter period to realize the effective signal as it is a modified complex pulse wave with rectangular impulses at that same rate. By default, the input reference trigger is meant to oscillate with the reference frequency, which is normally chosen to match the input's carrier frequency. The desired quarter period trigger is deduced from the reference trigger via frequency scaling.

c. In every quarter period, the image sensor's photodiodes integrate the intensity of the incident light. Except for an overhead, the light-sensitive proportion of the full period is configurable. The acquired signal in a single pixel forms the basic unit from which the lock-in output at that site is assembled via simple summation and subtraction. Although intermediate steps are executed in a different order, the output is strictly the same as when described in terms of multiplicative mixing with s_{ref} and convolutive filtering with h_{avg}.

5.2.3 Effective Signal Processing

The following paragraph offers an implementation-oriented model of the signal processing in a single pixel of the heliCam™ C4, which is more accurate than the previous analysis of ideal lock-in amplification. For advanced experiments, the implications of this specific implementation may become significant for an informed choice of camera settings and accurate interpretation of measurement results. The preceding explanation of the image sensor's operation principle implies two consequential deviations from the ideal; both the reference signal, s_{ref}, and the filter's impulse response, h_{avg}, differ from their ideal counterparts.

5.2.3.1 Mixing with a Pulse Wave

As argued above, a pulse wave is a good approximation of the effective reference signal of the heliCam™ C4. This pulsed approximation of s_{ref} can be represented analytically in a plethora of ways. The option chosen here is conceptually close to the hardware implementation. s_{ref} is viewed as the convolution of the rectangular sensor response in a single quarter period and a modified Dirac comb (see Fig. 5.5 a).

$$s_{ref}(t) = 2 \cdot rect\left(\frac{t}{\frac{p_s}{4f_{ref}}}\right) * \left(e^{-i2\pi f_{ref} t} \cdot \sum_{n \in \mathbb{Z}} \delta\left(t - \frac{n}{4f_{ref}}\right)\right) \tag{5.56}$$

The sensor is uniformly responsive in a fraction p_s of the full quarter period $(4 \cdot f_{ref})^{-1}$, which determines the width of the first, "boxcar"-like function. The spacing between spikes of the modified Dirac comb is a quarter period, indicating the timing of individual acquisitions. Spikes are alternately real and imaginary. Their sign flips after each consecutive pair to account for subtraction and summation quarter-periodic measurement results.

An advantage of this complicated representation is that its frequency domain representation can be broken down to basic relations (5.20), (5.23), (5.24) and (5.34), found in the summary on the Fourier Transform.

$$\begin{aligned} S_{ref}(f) &= \mathcal{F}\left\{2 \cdot rect\left(\frac{t}{\frac{p_s}{4f_{ref}}}\right)\right\}(f) \times \mathcal{F}\left\{e^{-i2\pi f_{ref} t} \times \sum_{n \in \mathbb{Z}} \delta\left(t - \frac{n}{4f_{ref}}\right)\right\}(f) \\ &= 2\sum_{k \in \mathbb{Z}} p_s sinc\left(p_s\left(k - \frac{1}{4}\right)\right) \times \delta\left(f + f_{ref} - 4kf_{ref}\right) \end{aligned} \tag{5.57}$$

In contrast to the ideal case, the reference signal comprises also non-zero components at frequencies other than $(-)1 \times f_{ref}$, namely at $(+)3 \times f_{ref}$, $(-)5 \times f_{ref}$, $(-)7 \times f_{ref}$ and so forth. They are called odd harmonics of the fundamental frequency f_{ref}. The $sinc$ term determines the magnitude with which these frequencies appear in the reference signal. Although higher frequencies components tend to be attenuated more, not all higher odd harmonics are insignificant compared to the first harmonic. The potential to selectively reduce their prominence is limited by the fact that p_s, being the fraction of the quarter period in which photodiodes are sensitive, cannot exceed 1.

Mixing is described analogous to (5.6) in time- and to (5.43) in frequency domain (see Fig. 5.5 b).

$$s_{mix}(t) = s_{in}(t) \times s_{ref}(t) = s_{in}(t) \times 2\sum_{n \in \mathbb{Z}} e^{-i2\pi\frac{n}{4}} rect\left(\frac{4f_{ref}t - n}{p_s}\right) \tag{5.58}$$

$$\Big\downarrow \mathcal{F}$$

$$S_{mix}(f) = S_{in}(f) * S_{ref}(f) = 2\sum_{k \in \mathbb{Z}} p_s sinc\left(p_s\left(k - \frac{1}{4}\right)\right) \times S_{in}\left(f + f_{ref} - 4kf_{ref}\right)$$

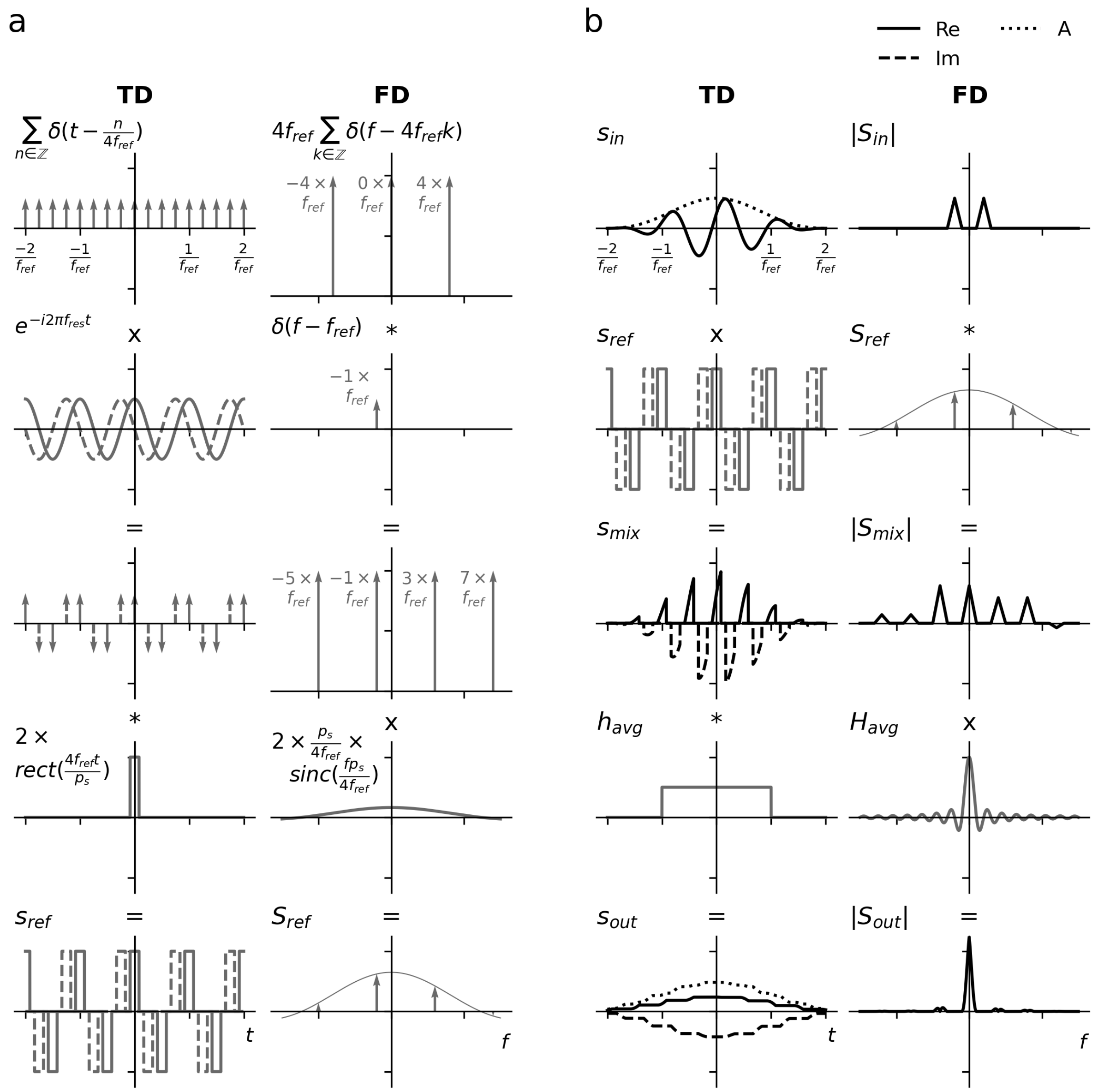


Fig. 5.5: Effective Reference Signal and Dual-Phase Demodulation

In both a. and b., time-domain (TD) signals $s.(t)$ are depicted left alongside their frequency domain (FD) representations $S.(f)$ on the right.

a. Synthesis of the Effective Reference Signal in TD (left) and FD (right) from elementary components.

   In TD, a Dirac comb indicating quarter periodic sampling is multiplied with the ideal complex reference oscillation to indicate how individual samples are weighted when summed together. The result is convolved with the rectangular sensor sensitivity response in a single quarter period to yield the effective reference signal, s_{ref} of the image sensor heliSens™ S4. s_{ref} differs from the ideal case in that it contains non-zero frequency components at odd harmonics of the fundamental reference frequency, f_{ref}. Moreover, the salience of all these components, inclusively that at reference frequency, is given by the $sinc$ of their frequency.

b. Demodulation of an amplitude modulated input with a complex pulse wave as reference and a rectangular filter.

   The demodulation process is analogous to the ideal case but for a different reference signal and filter. The filter width is also the sampling period. This final sampling step is not shown. In contrast to the ideal case, mixing not only shifts the input spectrum by the reference frequency. Each odd harmonic component in the reference signal produces a frequency-shifted copy, according to its own magnitude. Input frequency components around each odd multiple of the reference frequency end up in the baseband. The lock-in amplifiers that use a pulse wave such as the heliCam™ C4 are therefore sensitive to odd harmonics of the reference frequency.

5.2.3.2 Rectangular Filter and Sampling

The frequency response of the rectangular averaging filter (5.52) is a $sinc$ according to (5.24).

$$H_{avg}(f) = T \cdot sinc(T \cdot f) \tag{5.59}$$

The (continuous) output signal is obtained by convolution of the mixed signal s_{mix} with the filter's impulse response h_{avg} (see Fig. 5.5 b) like in the ideal case (5.7). In the frequency domain, again, this corresponds to a multiplication with the filter's frequency response H_{avg}.

$$\begin{aligned} s_{out}(t) &= h_{avg}(t) * s_{mix}(t) \\ &= 2 \cdot rect\left(\frac{t}{T}\right) * \left(s_{in}(t) \times \sum_{n\in\mathbb{Z}} e^{-i2\pi\frac{n}{4}} rect\left(\frac{4f_{ref}t - n}{p_s}\right)\right) \end{aligned} \tag{5.60}$$

$$\Big\downarrow \mathcal{F}$$

$$\begin{aligned} S_{out}(f) &= H_{avg}(f) \times S_{mix}(f) \\ &= 2 \cdot T \cdot sinc(T \cdot f) \times \sum_{k\in\mathbb{Z}} p_s sinc\left(p_s\left(k - \frac{1}{4}\right)\right) \cdot S_{in}\left(f + f_{ref} - 4kf_{ref}\right) \end{aligned}$$

The low-pass filter still extracts the baseband after the input is subjected to down-mixing. Yet unlike an ideal filter, not all the baseband components are treated with precise uniformity. They rather pass with the $sinc$ of the frequency. Moreover, the filter cannot selectively remove generally undesirable parts of the signal - associated with higher odd harmonics - from the baseband.

The output of the heliCam™ C4 is not actually continuous but expression (5.60) is sampled with time constant T, the filter width. In the frequency domain, sampling is a periodization of the spectrum and aliasing occurs if the modulation signal's highest frequency is above the Nyquist frequency.

5.2.4 Background Suppression

Lock-in amplification, as presented above, is in principle insensitive to large DC offsets on input signals (see Fig. 5.6 a). By measuring differences in input intensity at different moments during the period, a constant offset theoretically cancels out.

In practice, the dynamic range of image sensors is limited (see Fig. 5.6 b). If photodiodes register too many photon arrivals in one go, they saturate. As uniformly saturated measurements propagate through the in-pixel processing, they can erroneously result in an absence of AC signal.

To circumvent this issue, the heliCam™ C4 offers a background suppression mechanism (see Fig. 5.6 c). If background suppression is enabled, the first period in each frame is reserved to register the input intensity (at the end of the period). This value is then subtracted as background from the input during the rest of the frame, when lock-in amplification is performed - thus effectively preventing saturation due to large constant background signals. Suppressing the background is only recommended if the DC offset is much larger than the AC amplitude.

This background suppression is referred to as AC coupling because its implementation is analogous to the namesake recording modality of a conventional lock-in amplifier or an oscilloscope. Consequentially, the operation mode without background suppression is called DC coupling.

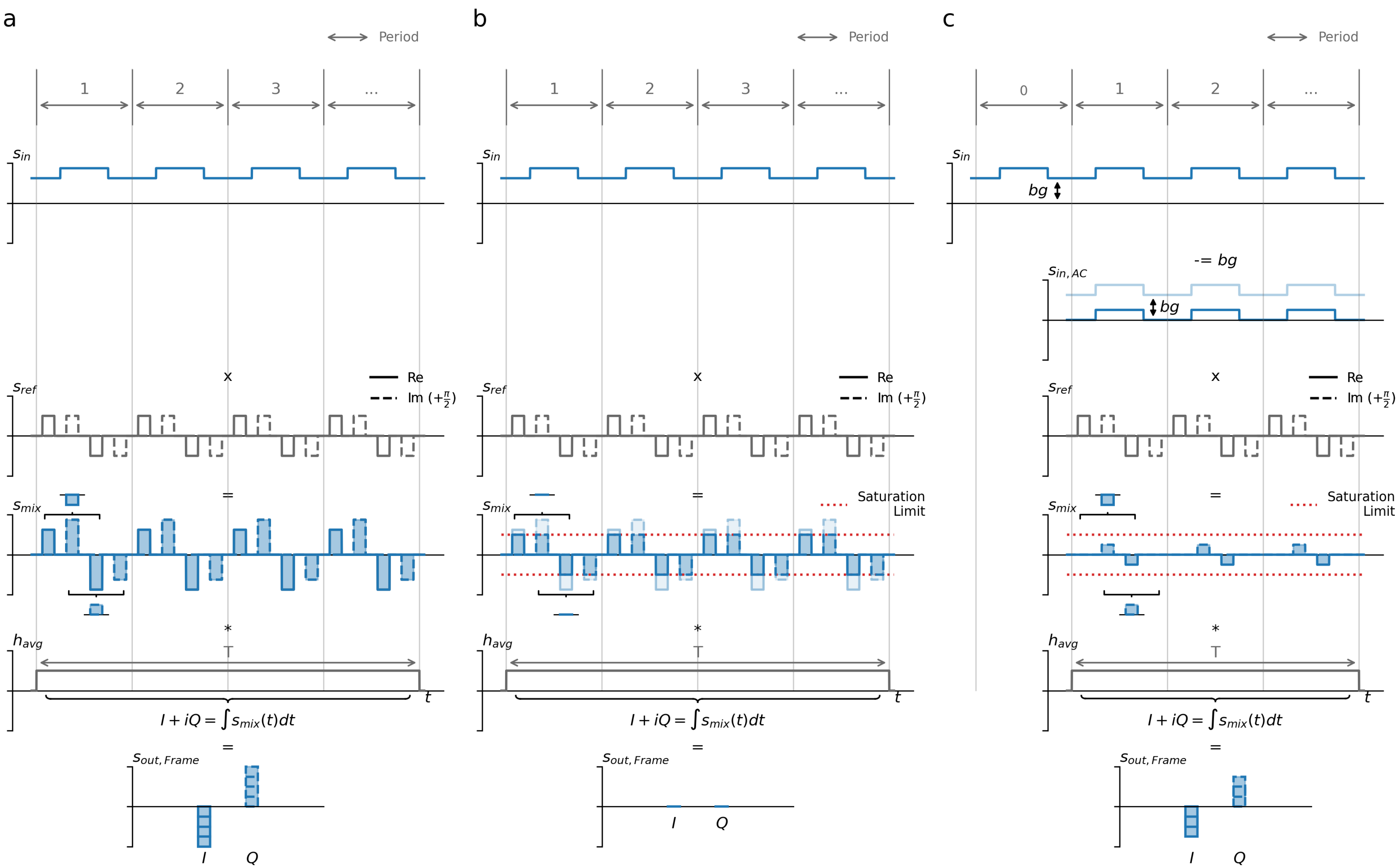


Fig. 5.6: Background Suppression / AC-Coupling
a) Demodulation of square wave without saturation limit. b) If the input's DC background is large, photodiodes saturate in each quarter periodic measurement. Integrating them into a frame erroneously produces no AC-signal. c) With enabled AC coupling, the background is measured in the frame's first period and subtracted from subsequent frames to avoid saturation.

5.2.5 Reference Signal Synthesis

Once the functionality of the sensor is understood, the parametrization of the effective reference signal through lock-in camera features can be explained clearly (cf. Fig. 6.1). Such parameters and important selection options are printed in **bold** below.

As described earlier, the basic building block of the sensor schedule is the quarter period. The pace of the reference signal, to which the input is compared, is determined by a trigger indicating the start of each new quarter period. How this trigger is obtained, depends on the **Reference Source Type:**

- **Internal:** The heliCam™ 's internal clock signals the onset of each quarter period. Another quarter period is automatically initiated when the sensor operation in the preceding one is finished. The fixed time it takes the sensor to run a quarter periodic measurement sequence, t'_{qp}, is derived from the configurable **Reference Frequency, f'$_{\mathbf{ref}}$**.

$$t'_{qp} = \frac{1}{(4 \cdot \mathbf{f'_{ref}})} \quad (\textbf{internal}\, reference) \tag{5.61}$$

  In this case, the **Reference Frequency** feature value, **f'$_{\mathbf{ref}}$**, corresponds directly to the frequency of the effective reference signal, f_{ref}. Equivalently, t'_{qp} coincides with the effective quarter period duration, t_{qp}.

- **External:** A reference input (rect wave, 0-5 V) from an external source, potentially processed camera-internally, triggers the onset of a new quarter period in the responsive period after the completion of the fixed sensor operation sequence in its predecessor. This trigger – and not the set **Reference Frequency** – dictates s_{ref}'s effective frequency in the external mode. Additional parameters influence the effective reference signal.

  - The **Reference Frequency Scaler** multiplies or divides the frequency of the trigger input by a select factor, **M** - in addition to a multiplication by four since the sensor needs indication of the quarter period rather than the period onset. With all factors **M** other than "DivideBy4", establishing the reference frequency thus involves averaging incoming discrete pulses (evaluated once immediately prior to the onset of the recording). Alone with the setting **M** = "DivideBy4" is the incoming signal directly routed to the sensor, where each pulse triggers a new quarter period.
  - The **Expected Frequency Deviation**, **d**, gives a security margin that is necessary should the reference trigger's frequency be unsteady. If a trigger signal arrives too early when the sensor is still busy, the impulse is missed. This introduces an error, which is prevented by accounting for the expected frequency deviation in the computation of the fixed duration of sensor activity per quarter period t'_{qp}. The minimal effective quarter period duration, t_{qp} is hence given by t'_{qp}.

$$t_{qp}^{min} = t'_{qp} = \frac{1}{(4 \cdot \mathbf{f'_{ref}} \cdot \mathbf{d})} \quad (\textbf{external}\, reference) \tag{5.62}$$

  Increased trigger timing error tolerance comes at the cost of a reduced signal amplitude. **Expected Frequency Deviation** is ignored in the internal reference mode.

The camera feature **Sensitivity** determines the fraction of t'_{qp} during which the sensor is light-sensitive and corresponds to p_s from the previous paragraph.

$$t_s = p_s \times t'_{qp} \tag{5.63}$$

, were t_s denotes the photoreceptive portion of the quarter period. Viewed like this, the **Sensitivity** controls the duty cycle of the effective reference pulse wave.

Note: The heliSens™ S4 has a clock frequency of 80 MHz $\Rightarrow$ clock cycle, t_c = 12.5 ns. Thus, actually feasible **Reference Frequency** values, $\mathbf{f'_{ref}}$, are inverse multiples of $t_c \times 4$ - to account for all quarter periods.

$$\mathbf{f'_{ref}} = \frac{1}{n \cdot 4 \cdot t_c},\; n \in \left\{146,\; ..., 2^{16}\right\} \Rightarrow \Delta\mathbf{f'_{ref}} = \frac{\mathbf{f'_{ref}}}{4 \cdot t_c \cdot \mathbf{f'_{ref}}^{-1}} - \mathbf{f'_{ref}} \approx 4 \cdot tc \cdot \mathbf{f'_{ref}}^2 \tag{5.64}$$

In **Internal** reference mode, the effective reference frequency, f_{ref}, is restricted to these values. With an **External** reference, other frequencies may be fed in, but individual trigger pulses are registered only with a time resolution of $\pm t_c$. This can produce a period-to-period jitter of the effective f_{ref}.

CHAPTER

SIX

GRAPHICAL SUMMARY

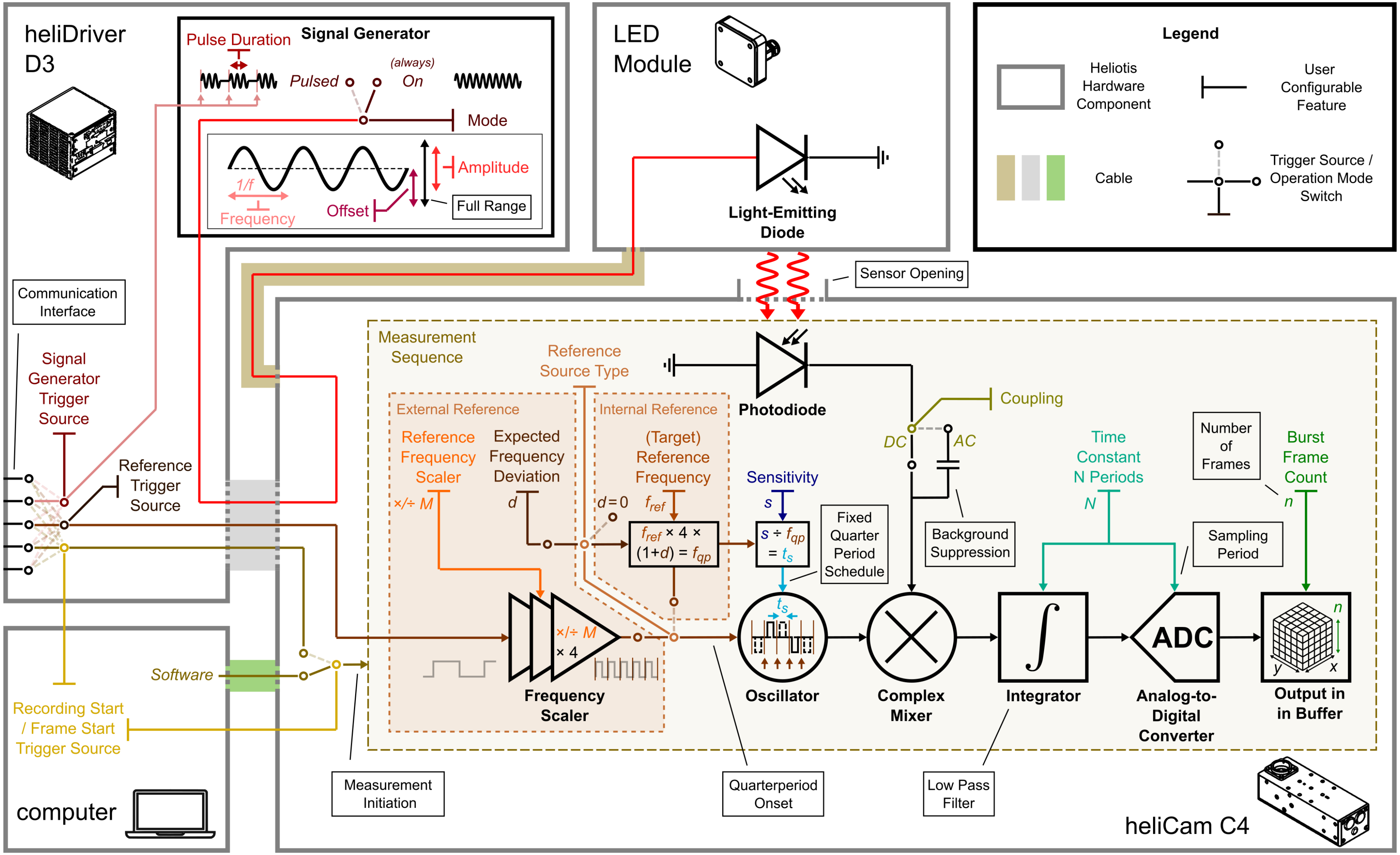


Fig. 6.1: Schematic Summary of Principal Operation Modes and User-Configurable Features

The heliCam™ C4 can be employed in different operation modes. Fig. 6.1 summarizes the most important switching points between them. Additionally, it shows other critical configurable lock-in camera features.

- For testing purposes, the heliCam™ C4 can be fed with a well-controlled optical input signal emitted by the Heliotis LED module. To that end, the signal generator unit in the heliDriver™ D3 can create a sinusoid current output, which is redirected to the LED via the heliCam™ C4 and drives its illumination.

  Three main signal generator modulation modes are available.

  - The signal generator modulation can be operated in the always **On** mode, producing AC and DC output continuously.
  - The amplitude modulation can be set to **Off**, so that the signal generator produces only DC offset. This is useful for Fixed Pattern Noise (FPN) correction.
  - Alternatively, there is the **Pulsed** mode, in which oscillating bursts, brought about by the external **Signal Generator Trigger**, are interrupted by period with constant light intensity.

  Certain features, such as the signal generator's **Pulse Duration** or the **Signal Generator Trigger Source** determining the trigger signal's source, are specific to the last mode. Others, such as the **Frequency**, (peak-to-peak) **Amplitude** and the **Offset** of the input sinusoid are common in all configurations. Both **Amplitude** and **Offset** are indicated in percent of the signal generator's full range.

- A new measurement can be initiated by an internal trigger from software or fed in via a pin on the heliDriver™ D3's communication interface.

- The heliCam™ C4 can be used with **Internal** or **External** reference, which determines if the clock signal driving the demodulation, is produced internally or externally. The switch between these two operating modes is set by the feature **Reference Source Type**.

  - If the reference source is set to **Internal**, the heliCam™ C4 determines the duration of the sensor operation in each quarter period according to the feature **Lock-In Actual Reference Frequency**. Another quarter period is immediately initiated once the sensor has completed its scheduled operation in the preceding one.
  - In the **External Reference** mode, a pulse wave (0-5 V) must be supplied to the camera via the heliDriver™ D3's communication interface. By default, it is expected to oscillate at the reference frequency. However, you have the option of setting a frequency multiplication or division factor with the feature **Reference Frequency Scaler**. Behind the scenes the input frequency (evaluated once immediately before measurement onset) is scaled with an additional multiplication factor four, such that the trigger signals the beginning of a new quarter period, rather than a period. Only with the setting "DivideBy4" is frequency scaling effectively disabled and the reference trigger signal is directly relayed to the sensor. Additional features are only active with the **External Reference** mode enabled. By setting an **Expected Frequency Deviation**, for instance, you may artificially shorten the time per quarter period during which the camera sensor is busy and unresponsive to trigger signals. In this fashion, you can prevent missing early trigger impulses if your trigger signal is unsteady.

- The **Sensitivity** determines during which fraction of a quarter period, the sensor is light-sensitive.

- The combined information about the onset of a quarter period and the sensor activity within it determines a "dual-phasic", complex effective reference signal. The first step of the sensor action can be thought of as multiplying this effective reference signal with the optical input in a mixing step.

- Setting the **Coupling** to **AC** enables background suppression. The potentially large DC background is hence removed prior to mixing at the cost of an integration cycle.

- The function of the feature **Time Constant N Periods** is twofold. It determines the duration of the rectangular filter that is applied to result of mixing and, at the same time, the sampling period.

- Finally, the feature **Burst Frame Count** determines the number of frames acquired in a measurement.

CHAPTER

SEVEN

WORLDWIDE SUPPORT

If you have a problem that you are unable to solve or have technical questions beyond the scope of this user manual, do not hesitate to contact Heliotis Support for further assistance.

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E: support@heliotis.com

I: www.heliotis.com

CHAPTER

EIGHT

DOCUMENT HISTORY

Version	Date	Changes	Responsible
1.0.0	03-07-2023	Initial version	bm
1.0.1	06-03-2024	Minor corrections and additional specifications Added document versioning Update reference to code examples Full description of light control options Ensure compatibility with new heliCam C4M	bm

CHAPTER

NINE

ANNEX

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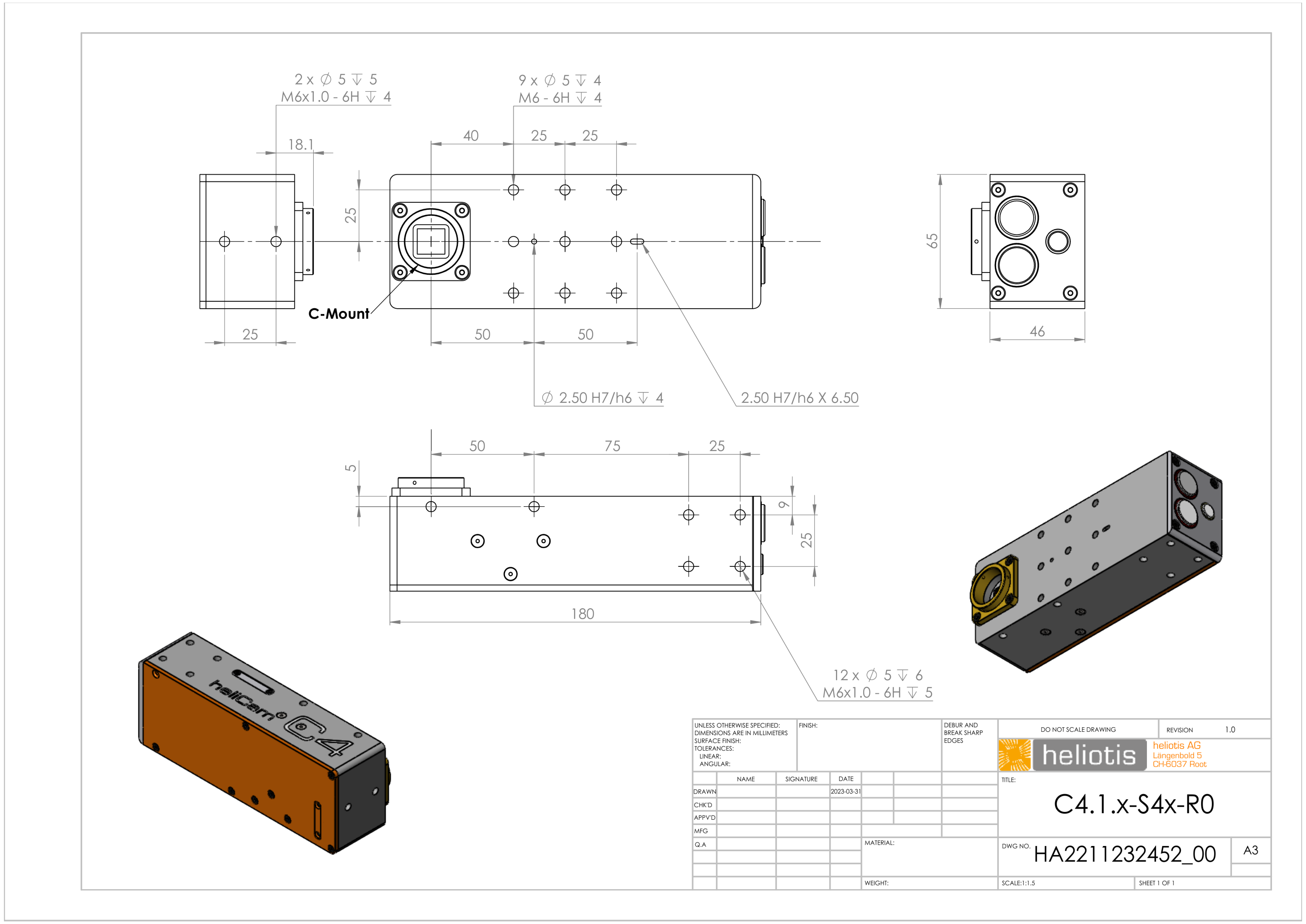
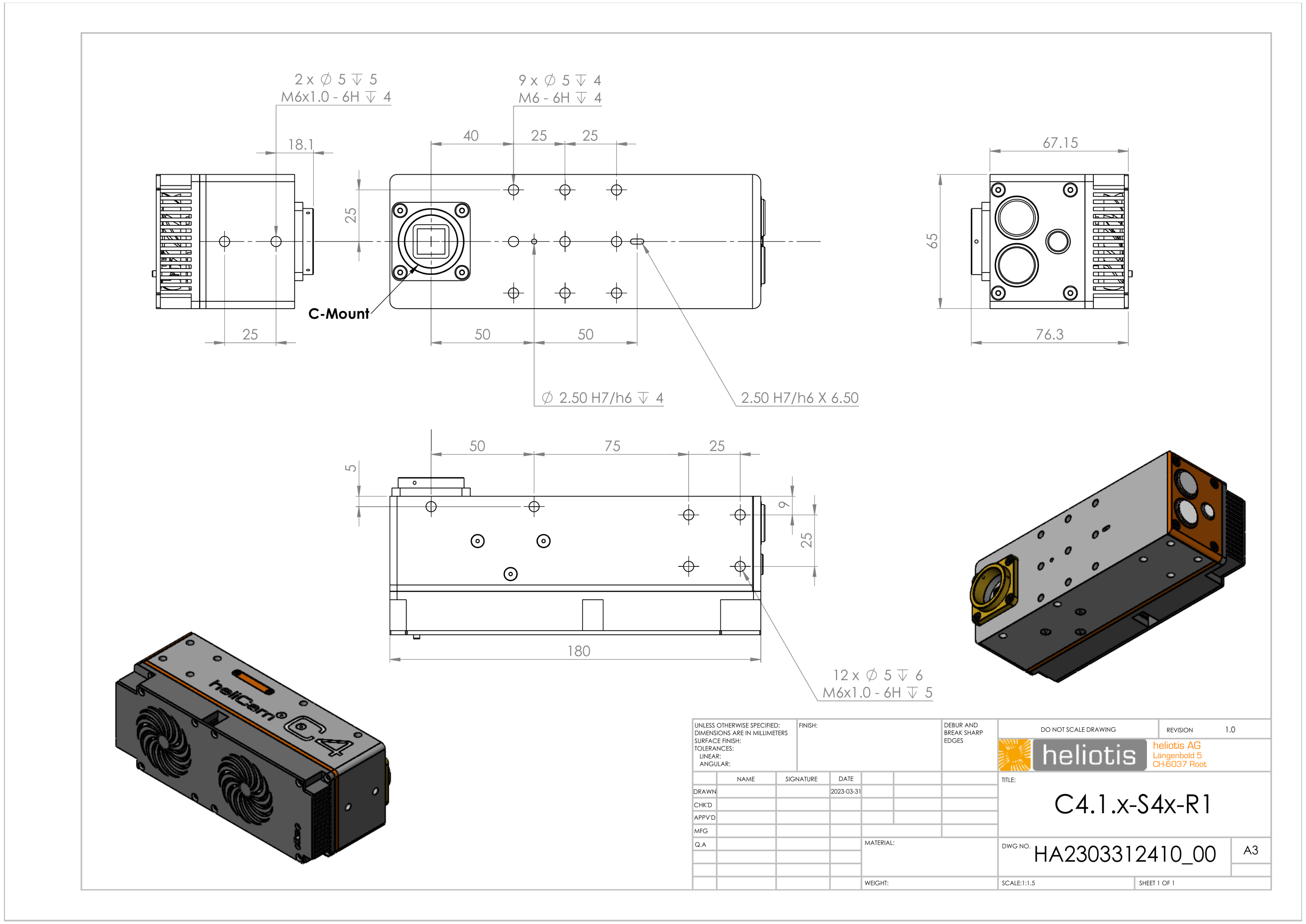
9.1.1 heliCam™ C4

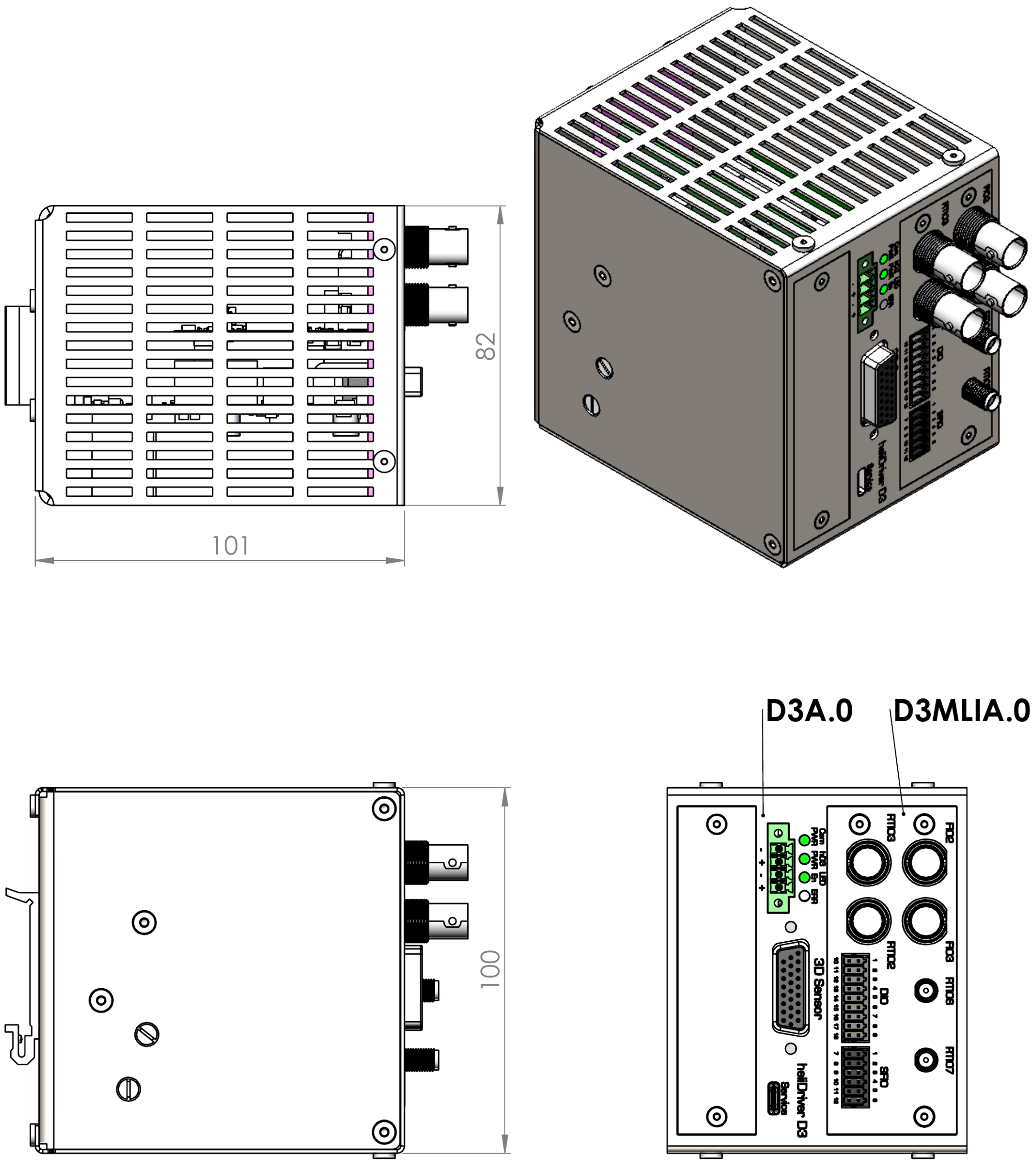
9.1.1.1 C4.1.x-S4xx-R0



9.1.1.2 C4.1.x-S4xx-R1



9.1.2 heliDriver™ D3 with LIA Module



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APPV'D						
MFG						
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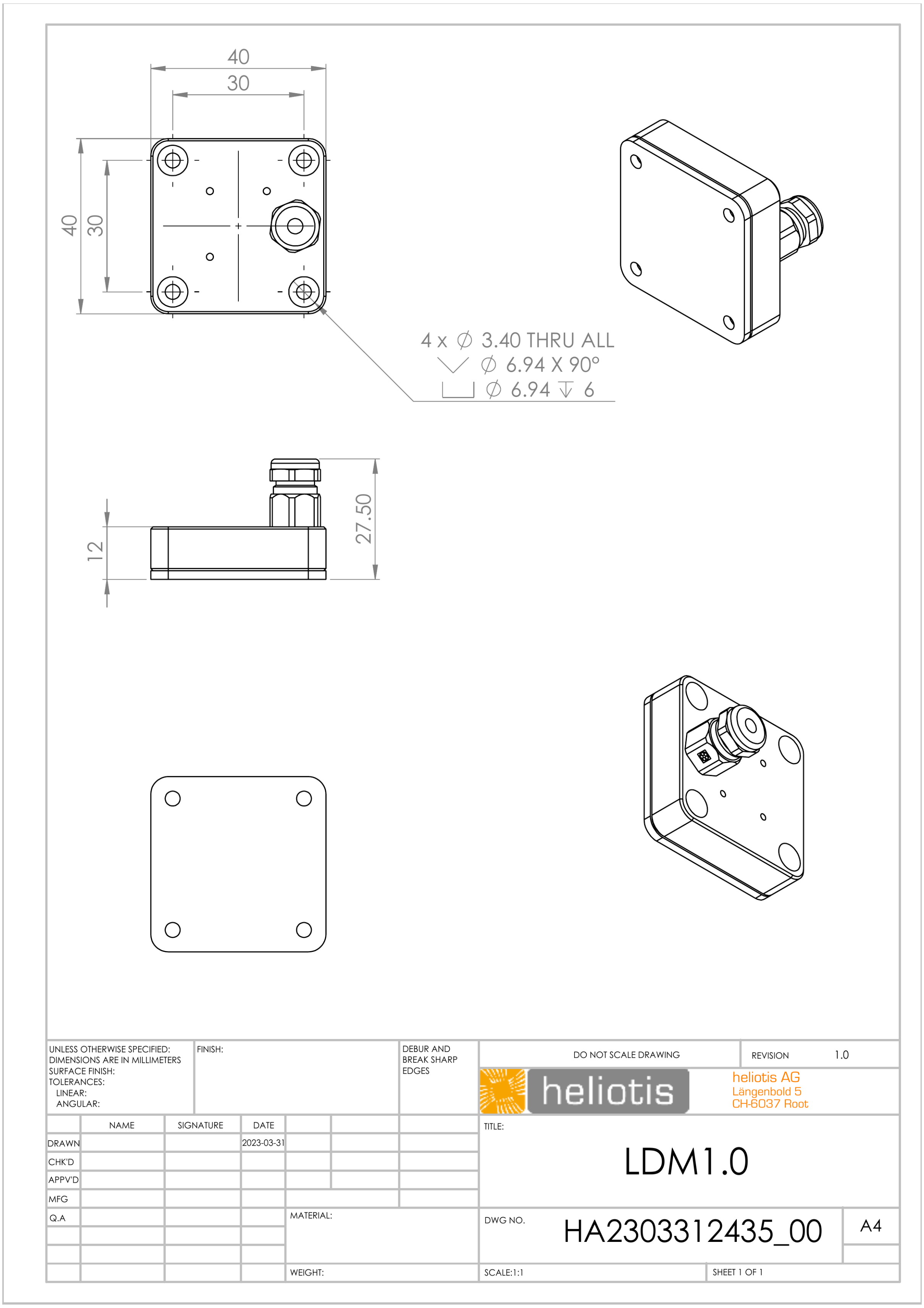
9.1.3 Heliotis LED Module



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