C4 Series

Scientific CMOS Camera

User’s Guide

moravian instruments

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Introduction

Thank you for choosing the Moravian Instruments camera. The C4 series of cooled scientific CMOS cameras were developed for imaging under extremely low-light conditions in astronomy, microscopy and similar areas.

Mechanical design of this series inherits from earlier CCD-based G4 Mark II cameras, which makes the C4 camera line fully compatible with vast range of telescope adapters, off-axis guider adapters, filter wheels, Camera Ethernet adapters, guiding cameras etc.

Rich software and driver support allow usage of C4 camera without necessity to invest into any 3rd party software package thanks to included free SIPS software package. However, ASCOM (for Windows) and INDI (for Linux) drivers and Linux driver libraries are shipped with the camera, provide the way to integrate C4 camera with broad variety of camera control programs.

The C4 cameras are designed to work in cooperation with a host Personal Computer (PC). As opposite to digital still cameras, which are operated independently on the computer, the scientific cooled cameras usually require computer for operation control, image download, processing and storage etc. To operate the camera, you need a computer which:

1. Is compatible with a PC standard and runs modern 32 or 64-bit Windows operating system.
2. Is an x86 or ARM based computer and runs 32 or 64-bit Linux operating system.

   Drivers for 32-bit and 64-bit Linux systems are provided, but the SIPS camera control and image processing software, supplied with the camera, requires Windows operating system.

3. Support for x64 based Apple Macintosh computers is also included.

   Only certain software packages are currently supported on Mac.

C4 cameras are designed to be attached to host PC through very fast USB 3.0 port. While C4 cameras remain compatible with older (and slower) USB 2.0 interface, image download time is significantly longer.

Alternatively, it is possible to use the "Moravian Camera Ethernet Adapter" device. This device can connect up to four Cx (and CCD based Gx) cameras of any type (not only C4, but also C1, C2 and C3) and offers 1 Gbps and 10/100 Mbps Ethernet interface for direct connection to the host PC. Because the PC then uses TCP/IP protocol to communicate with the cameras, it is possible to insert WiFi adapter or other networking device to the communication path.

> Please note that the USB standard allows usage of cable no longer than approx. 5 meters and USB 3.0 cables are even shorter to achieve very fast transfer speeds. On the other side, the TCP/IP communication protocol used to connect the camera over the Ethernet adapter is routable, so the distance between camera setup and the host PC is virtually unlimited.

Download speed is naturally significantly slower when camera is attached over Ethernet adapter, especially when compared with direct USB 3 connection.

The C4 cameras need an external power supply to operate. It is not possible to run the camera from the power lines provided by the USB cable, which is common for simple imagers. C4 cameras integrate highly efficient CMOS sensor cooling, shutter and possibly filter wheel, so their power requirements significantly exceed USB line power capabilities. On the other side separate power source eliminates problems with voltage drop on long USB cables or with drawing of laptop batteries etc.

Also note the camera must be connected to some optical system (e.g. the telescope) to capture images. The camera is designed for long exposures, necessary to acquire the light from faint objects. If you plan to use the camera with the telescope, make sure the whole telescope/mount setup is capable to track the target object smoothly during long exposures.

C4 Camera Overview

C4 camera head is designed to be easily used with a set of accessories to fulfil various observing needs. There are variants differing in the cooling performance:

- Standard cooling
- Enhanced cooling (11 mm thicker due to increased heat sink)

Figure 1: Enhanced Cooling C4 Camera without filter wheel (left), with "M" size External filter wheel (middle) and with "L" size External filter wheel (right)

As opposed to smaller C2 and C3 camera models, which offer an option to integrate filter wheel into camera shell, large C4 camera sensors need square 50×50 mm filters, too big to fit into Internal filter wheel. So, using of External filter wheel is the only option for C4 cameras.

There are two sizes of the External filter wheels available:

- Medium "M" size wheel for 5 unmounted 50×50 mm square filters.
- Large "L" size wheel for 7 unmounted 50×50 mm square filters.

C4 Camera System

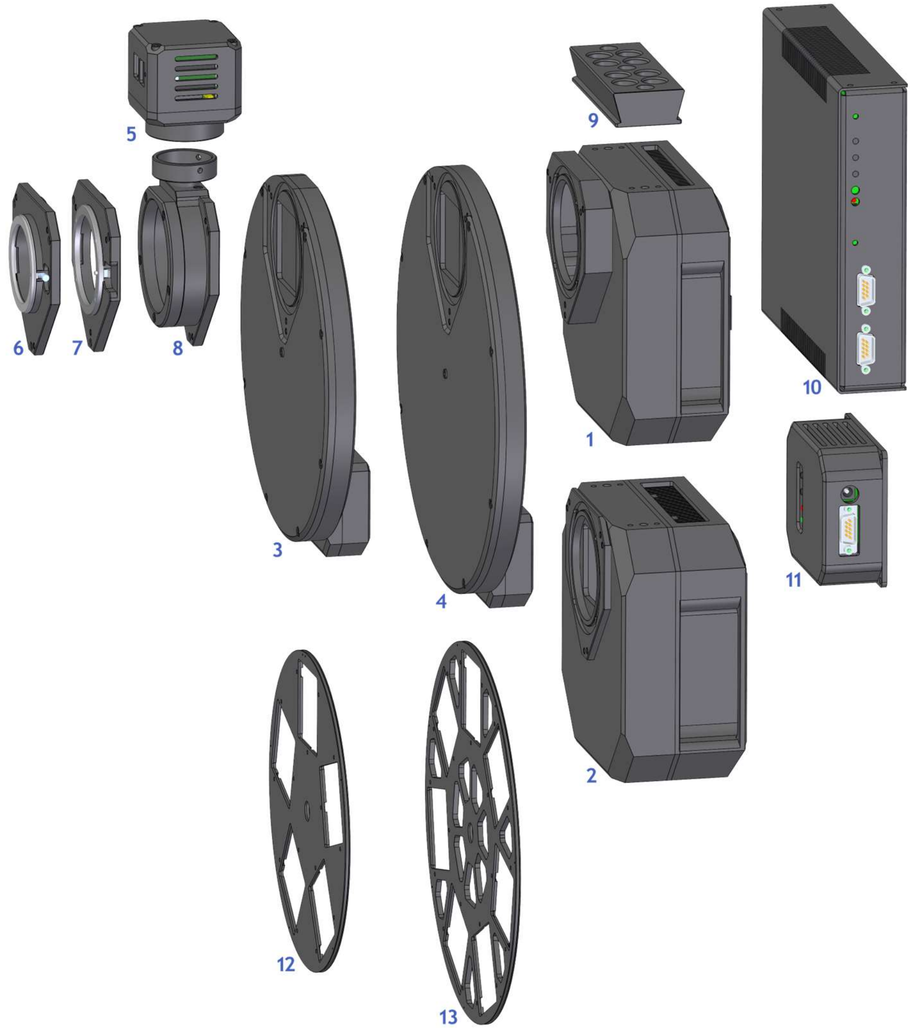


Figure 2: Schematic diagram of G4 camera system components

Components of C4 Camera system include:

1. C4 camera head with standard cooling
2. C4 camera head with Enhanced Cooling (EC) option

Both variants of camera head are capable to control the External Filter Wheel

3. External Filter Wheel “M” size (5 positions)
4. External Filter Wheel “L” size (7 positions)
5. C1 Guider camera

C1 cameras are completely independent devices with their own USB connection to the host PC. They can be used either on the OAG or on standalone guiding telescope.

C1 camera can share the Moravian Camera Ethernet Adapter with up to 3 other Cx or Gx cameras to be accessed over TCP/IP network.

6. Nikon bayonet adapter for Nikon compatible lenses
7. Canon EOS bayonet adapter for Canon compatible lenses
8. Off-Axis Guider with M68×1 thread adapter
9. 1.75” dovetail rail for C4 camera head
10. Moravian Camera Ethernet Adapter (x86 CPU)
11. Moravian Camera Ethernet Adapter (ARM CPU)

Moravian Camera Ethernet Adapter allows connection of up to four Cx cameras of any type on the one side and 1 Gbps Ethernet on the other side. This adapter allows access to connected Gx cameras using routable TCP/IP protocol over practically unlimited distance.

12. 5-positions “M” size filter wheel for 50×50 mm square filters
13. 7-positions “L” size filter wheel for 50×50 mm square filters

CMOS Sensor and Camera Electronics

C4 cameras are equipped with Gpixel GSENSE4040 CMOS detectors with resolution 4096 × 4096 pixels. Pixel size is 9 × 9 µm, which leads to almost 37 × 37 mm light sensitive area.

The GSENSE4040 sensor is equipped with 12-bit ADCs (Analog to Digital Converters) only. However, there are two sets of ADCs inside the sensor, each capable to digitize the image with different gain – one set of ADCs uses low-gain channel, while the second set uses high-gain channel. Both 12-bit outputs of each ADC set can be combined to single image with true 16-bit dynamic range (such combined image is often called 16-bit HDR for High Dynamic Range).

Camera Electronics

CMOS camera electronics primary role, beside the sensor initialization and some auxiliary functions, is to transfer data from the CMOS detector to the host PC for storage and processing. So, as opposite to CCD cameras, CMOS camera design cannot influence number of important camera features, like the dynamic range (bit-depth of the digitized pixels).

Sensor linearity

The sensors used in C4 cameras show very good linearity in response to light. This means the camera can be used for advanced research projects, like the photometry of variable stars and transiting exoplanets etc.

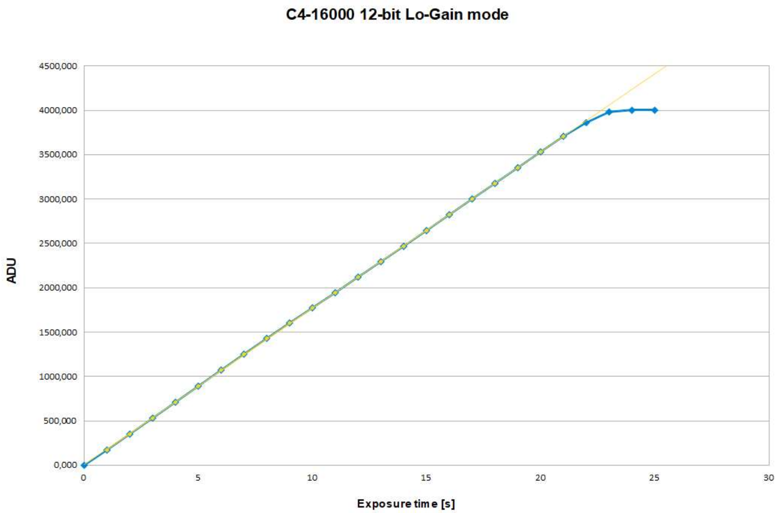


Figure 3: Response of GSENSE4040 sensor in 12-bit low-gain mode

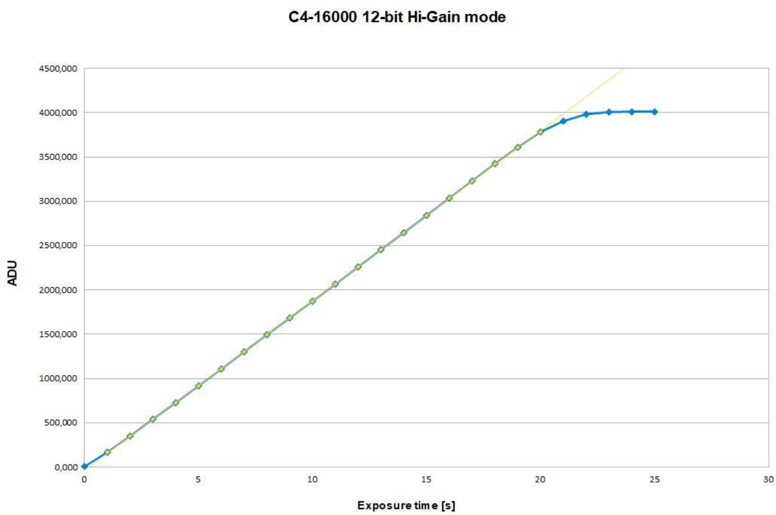


Figure 4: Response of GSENSE4040 sensor in 12-bit high-gain mode

Combination of both low-gain and high-gain digitization channels into single 16-bit HDR image is designed to carefully preserve linear response to light. What's more, resulting 16-bin image does not combine full dynamic range of both low-gain and high-gain channels, but takes only the perfectly linear portions of both channels. So, the linearity of the resulting 16-bit image is perfect within the full dynamic range of the sensor.

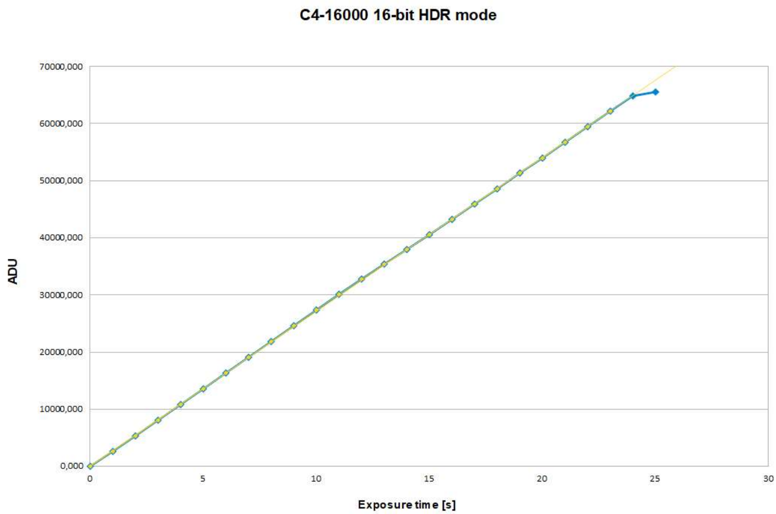


Figure 5: Response of GSENSE4040 sensor in 16-bit HDR mode

Download speed

C4 camera is equipped with on-board RAM, capable to hold multiple full-resolution frames. Downloading of the image to the host computer thus does not influence image digitization process, as the download only transfers already digitized images from camera memory.

Time needed to download single frame depends on the read mode and also whether fast USB3 or slower USB2 is used:

Read mode	12-bit low/high gain	16-bit HDR
USB 3.0	0.125 s	0.250 s
USB 2.0	0.797 s	1.578 s

Conversion factors and read noise

C4 cameras do not offer the users to set gain, beside the two fixed low-gain and high-gain channels. 16-bit HDR image covers whole sensor dynamic range and manipulating with gain would bring no additional benefits.

Read mode	12-bit high-gain	12-bit low-gain	16-bit HDR
Full well capacity	3540 e-	80000 e-	56600 e-
Conversion factor	0.85 e-/ADU	19.5 e-/ADU	0.85 e-/ADU
Read noise	3.9 e- RMS	34.5 e- RMS	3.9 e- RMS

Please note the values stated above are determined from acquired images using the SIPS software package. Results may slightly vary depending on the test run, on the particular sensor and other factors (e.g. sensor temperature, sensor illumination conditions etc.), but also on the software used to determine these values, as the method is based on statistical analysis of sensor response to light.

Exposure control

C4 cameras are capable of very short exposures, the shortest exposure time is approx. 21 µs. However, the sensor employs so-called “rolling shutter”. This means the exposure does not start over the whole sensor at once, but exposure of subsequent lines begins with 21 µs delay and the whole sensor is illuminated 8.6 ms after exposure starts. Similarly, end of exposure and pixel digitization is performed line by line with the same delay between lines.

There is no practical limit on maximal exposure length, but in reality, the longest exposures are limited by saturation of the sensor either by incoming light or by dark current (see the following chapter about sensor cooling).

Hardware binning

The used GSENSE4040 sensor implements 2×2 binning mode in hardware in addition to normal 1×1 binning.

However, the back-side illuminated version of this sensor GSENSE4040BSI does not implement any binning mode in hardware. Also, the camera driver and user’s applications offer much wider variety of binning modes up to 3×3 and 4×4 pixels as well as all combinations of asymmetrical binning modes 1×2, 1×3, 2×4 etc. This is why the camera driver performs all binning combinations in software and does not rely on the limited capabilities of the sensor hardware binning.

The negative side of software binning is the same download time like in the full-resolution 1×1 mode. For typical astronomy usage the small fraction of second download time is irrelevant, but for applications very sensitive to download time, the driver offers usage of the hardware 2×2 binning. This mode can be turned on and off using the parameter in the ‘cXusb.ini’ configuration file, located in the same directory like the ‘cXusb.dll’ driver DLL file itself.

```
[driver]
HWBinning = true
```

When the HWBinning parameter is set to true, GSENSE4040 hardware binning is used. This mode brings faster download time, but also introduces several restrictions:

1. Maximal binning is limited to 2×2, higher binning modes are not available.
2. Asymmetrical binning modes (1×2, 2×1) are not allowed.

Despite the number of pixels in the 2×2 binned image is ¼ of the full resolution image, the download time is not four-times lower. The sensor performs image read of the 2×2 binned image only two-times faster compared to full resolution image.

Hardware binning is supported by camera firmware version 6.6 and later. The Windows SDK supports the hardware binning from version 4.9 and the SIPS software package from version 4.0.

Sensor specifications

C4-16000 cameras are supplied with Class 1 sensors. The light gathering area of the GSENSE4040 sensors is divided into 4 quadrants, slightly differing in bias levels. This division may remain visible as slightly different background levels, especially when the overall scene illumination is low.

Such uneven background typically does not harm scientific measurements, as the differences are well beyond background noise. But aesthetic astro-photography can be negatively influenced if these differences are not removed during image processing.

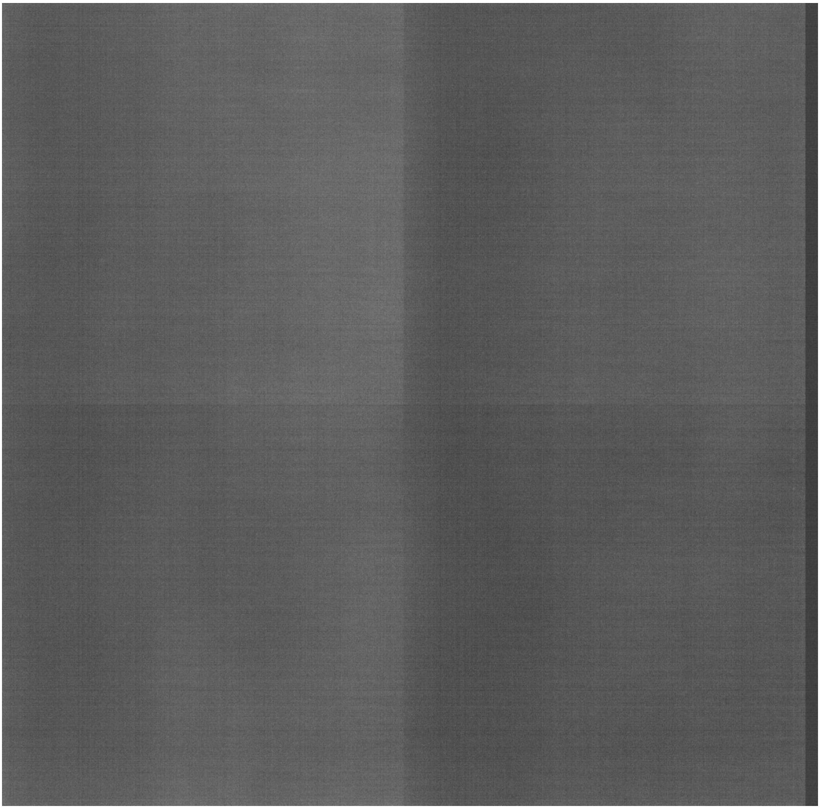


Figure 6: Bias frame of the GSENSE4040 sensor, showing 4 quadrants with slightly different levels. The dark stripe on the right is the black-level (overscan) area.

Overscan area

The GSENSE4040 sensor contains shielded pixels, returning black-level signal (also known as overscan area) in addition to normal illuminated pixels. There are 64 black-level pixels in each of 4096 rows. The C4-16000 camera includes these pixels into each image, so the resulting image width is 4096 + 64 = 4160 pixels. The 64 pixels wide stripe of black-level pixels is also visible on the image above.

However, the camera driver by default removes the overscan area and returns only illuminated area of 4096 × 4096 pixels to the user. This function is controlled by a parameter ‘C4Overscan’ in the section ‘[driver]’ of the driver configuration file ‘cXusb.ini’, located in the same directory like the ‘cXusb.dll’ driver DLL file itself.

```
[driver]
C4Overscan = false
```

When the parameter value is modified to ‘true’, image returned from camera will include the 64 pixels wide black-level overscan area to the right of the image.

Reading of both high-gain and low-gain images

The C4-16000 camera driver offers four read modes by default:

1. 16-bit HDR mode (default)
2. 12-bit High-Gain mode
3. 12-bit Low-Gain mode
4. 16-bit transformed Low-Gain mode

The first mode is a result of HDR combination of both low-gain and high-gain frames, the second and third mode returns either the high-gain part or low-gain part of the image.

However, the driver needs to read both high-gain and low-gain parts of the image at once to be able to combine them into HDR image. Unfortunately, it is not possible to just add a fifth read mode to return both uncombined parts to the user, as the image containing both parts are twice as big. Camera cannot change resolution upon mode changes.

The driver still allows reading of both high-gain and low-gain portions of the image, but it is necessary to restart the driver with the parameter ‘C4BothGains’ in the ‘[driver]’ section of the driver configuration file ‘cXusb.ini’ set to true.

```
[driver]
C4BothGains = true
```

If this parameter is set to true, the driver no longer allows changing of read modes, only single 12-bit read mode is available. Also, the C4-16000 camera resolution changes from 4096 × 4096 to 4096 × 8192 pixels (providing the C4Overscan = false; if it is true, returned image measures 4160 × 8192 pixels).

Returned images then contain high-gain frame in the lower portion of the image and high-gain frame in the upper portion of the image.

> Note:
>
> The FITS coordinate system should follow the standards common in mathematics, physics and elsewhere, which means the x-axis increases to the right and the y-axis increases up. The [0, 0] point is then the lower-left image corner. Unfortunately, many popular software packages do not follow this standard and places the [0, 0] point to the upper-left corner, which means the y axis increases in the top-down direction. So, in the standard FITS coordinates, the high-gain portion of the image begins at [0, 0] and the low-gain part is placed above it.

The ability to read both parts of the image was added for the special cases when the camera output needs some custom processing, but it is not needed for advanced calibration during regular imaging. We mentioned here only for completeness.

Cooling and power supply

Regulated thermoelectric cooling is capable to cool the CMOS sensor up to 35 °C below ambient temperature. The Peltier hot side is cooled by fan. The sensor temperature is regulated with ±0.1 °C precision. Cooling and precision regulation ensure the dark current does not ruin long exposures and allow proper image calibration.

The camera head contains two temperature sensors – the first thermometer measures directly the temperature of the CMOS sensor. The second one measures the temperature inside the camera shell.

Figure 7: Back side of the C4 camera head contains vents for two fans, cooling Peltir hot side

The cooling performance depends on the environmental conditions and also on the power supply. If the power supply voltage drops below 12 V, the maximum temperature drop is lower.

CMOS sensor cooling	Thermoelectric (Peltier modules)
Maximal cooling ΔT	~35 °C below ambient (Enhanced cooling)
	~30 °C below ambient (Standard cooling)
Regulated cooling ΔT	33 °C below ambient (Enhanced cooling)
	28 °C below ambient (Standard cooling)
Regulation precision	±0.1 °C
Hot side cooling	Forced air cooling (fans)

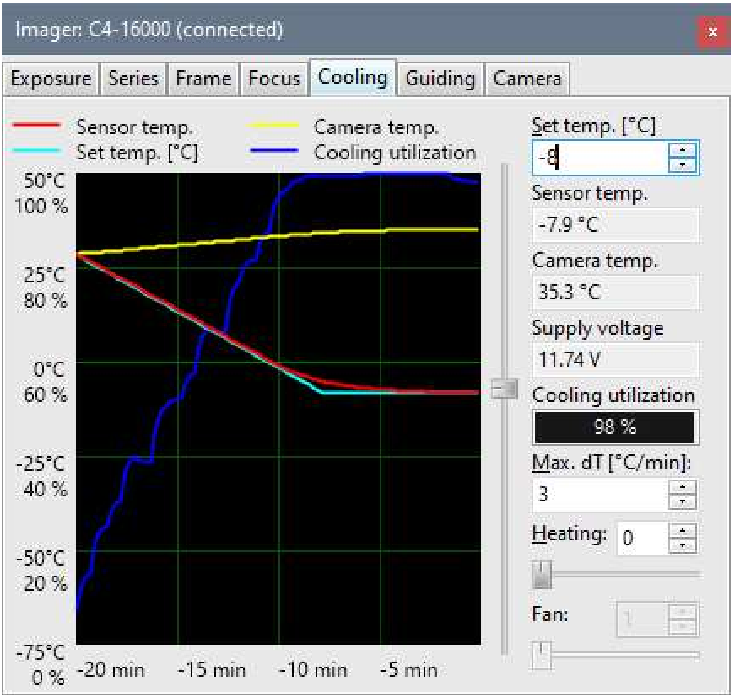


Figure 8: C4-16000EC camera reaching -35°C sensor temperature below ambient temperature

Maximum temperature difference between sensor and ambient air may be reached when the cooling runs at 100% power. However, temperature cannot be regulated in such case, camera has no room for lowering the sensor temperature when the ambient temperature rises. Typical temperature drop can be achieved with cooling running at approx. 90% power, which provides enough room for regulation.

Overheating protection

The C4 cameras are equipped with an overheating protection in their firmware. This protection is designed to prevent the Peltier hot side to reach temperatures above ~50°C – sensor cooling is turned off to stop heat generation by the hot side of the Peltier TEC modules.

Please note the overheating protection uses immediate temperature measurement, while the value of camera temperature, presented to the user, shows temperature averaged over a longer period. So, overheating protection may be engaged even before the displayed camera temperature reaches 50°C.

Turning the overheating protection on results in a drop in cooling power, a decrease in the internal temperature of the camera and an increase in the temperature of the sensor. However, when the camera cools its internals down below the limit, cooling is turned on again. If the environment temperature is still high, camera internal temperature rises above the limit an overheating protection becomes active again.

Please note this behavior may be mistaken for camera malfunction, but it is only necessary to operate the camera in the colder environment or to lower the desired sensor delta T to lower the amount of heat generated by the Peltier modules.

The overheating protection is virtually never activated during real observing sessions, even if the environment temperature at night reaches 25°C or more, because camera internal temperature does not reach the limit. But if the camera is operated indoors in hot climate, overheating protection may be activated.

Power supply

The 12 V DC power supply enables camera operation from arbitrary power source including batteries, wall adapters etc. Universal 100-240 V AC/50-

60 Hz, 60 W “brick” adapter is supplied with the camera. Although the camera power consumption does not exceed 55 W, the 60 W power supply ensures noise-free operation.

Warning:

The power connector on the camera head uses center-plus pin. Although all modern power supplies use this configuration, always make sure the polarity is correct if you use own power source.

Camera head supply	12 V DC
Camera head power consumption	<8 W without cooling
	47 W maximum cooling
Power connector	5.5/2.5 mm, center +
Adapter input voltage	100-240 V AC/50-60 Hz
Adapter output voltage	12 V DC/5 A
Adapter maximum power	60 W

Power consumption is measured on the 12 V DC side. Power consumption on the AC side of the supplied AC/DC power brick is higher.

The camera contains its own power supplies inside, so it can be powered by unregulated 12 V DC power source – the input voltage can be anywhere between 10 and 14 V. However, some parameters (like cooling efficiency) can degrade if the supply drops below 12 V.

C4 camera measures its input voltage and provides it to the control software. Input voltage is displayed in the Cooling tab of the Imaging Camera tool in SIPS. This feature is important especially if you power the camera from batteries.

Figure 9:Figure 8: 12 V DC/5 A power supply adapter for the C4 camera

Mechanical Specifications

Compact and robust camera head measures only 154×154×65 mm (approx. 6×6×2.6 inches) for the model with standard cooling. Enhanced cooling increases camera depth by 11 mm.

The head is CNC-machined from high-quality aluminum and black anodized. The head itself contains USB-B (device) connector and 12 V DC power plug, no other parts (CPU box, USB interface, etc.), except a “brick” power supply, are necessary. Another connector allows control of optional external filter wheel. Integrated mechanical shutter allows streak-free image readout, as well as automatic dark frame exposures, which are necessary for unattended, robotic setups.

Internal mechanical shutter	Yes, blade shutter
Shortest exposure time	21 μs (electronic shutter)
Longest exposure time	Limited by chip saturation only
Head dimensions	154×154×65 mm (standard cooling)
	154×154×76 mm (enhanced cooling)
Back focal distance	33.5 mm (base of adjustable adapters)
Standard cooling weight	1.6 kg (without filter wheel)
	2.5 kg (with “M” External filter wheel)
	2.8 kg (with “L” External filter wheel)
Enhanced cooling weight	1.8 kg (without filter wheel)
	2.7 kg (with “M” External filter wheel)
	3.0 kg (with “L” External filter wheel)

C4 cameras use electronic shuttering to control exposures. Mechanical shutter is used only to cover the sensor when acquiring dark or bias frames.

Back focus distance is measured from the sensor to the base on which adjustable adapters are mounted. Various adapters then provide back focal distance specific for the particular adapter type (e.g. Canon EOS bayonet adapter back focal distance is 44 mm).

Stated back focal distance already calculates with glass permanently placed in the optical path (e.g. optical window covering the sensor cold chamber).

Mechanical shutter

C4 cameras are equipped with mechanical shutter, which is very important feature allowing unattended observations (fully robotic or just remote setups). Without mechanical shutter, it is not possible to automatically acquire dark frames, necessary for proper image calibration.

Mechanical shutter in the C4 cameras is designed to be as reliable as possible, number of open/close cycles is virtually unlimited, because there are no surfaces rubbing against each other. The price for high reliability is slow shutter motion. Luckily, mechanical shuttering is not necessary for exposure control, only for taking dark frames and possibly bias frames – all used CMOS sensors are equipped with electronic shuttering.

Therefore, camera firmware optimizes the shutter operation to avoid unnecessary movements. If a series of light images is taken immediately one after another, the shutter remains open not to introduce quite significant delay of the close/open cycle between each pair of subsequent light images. In the case next image has to be dark or bias frame, shutter closes prior to dark frame exposure and vice versa – shutter remains closed if a series of dark frames is acquired and opens only prior to next light frame. If no exposure is taken for approximately 2 seconds while the shutter is open (this means after a light image exposure), camera firmware closes the shutter to cover the sensor from incoming light.

Camera without filter wheel

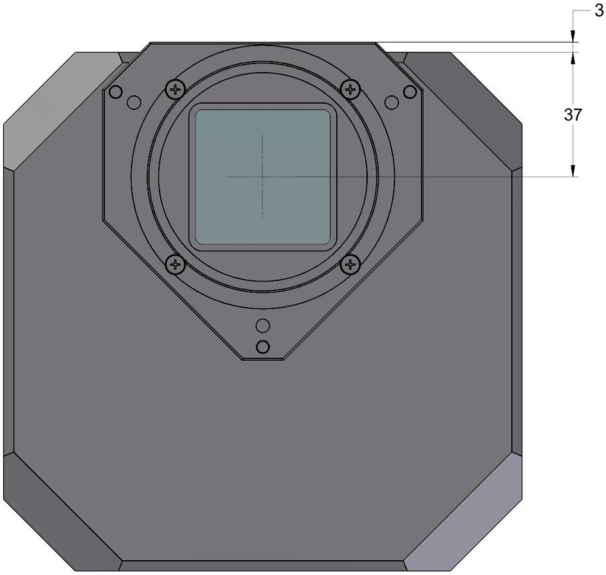


Figure 10: C4 camera head front view dimensions

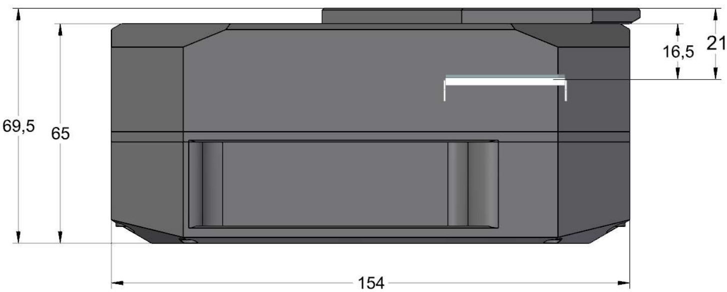


Figure 11: C4 camera head with thin adapter base side view dimensions

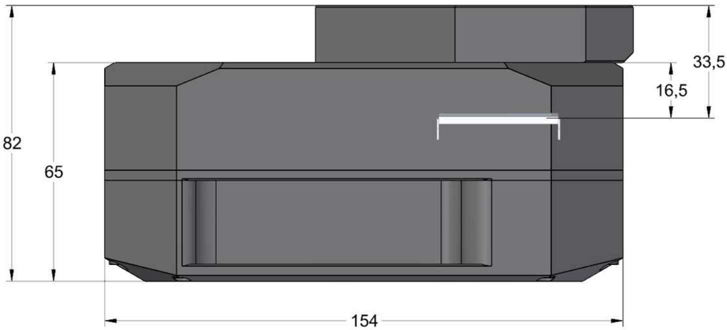


Figure 12: C4 camera head with thick adapter base, compensating the thickness of the External Filter Wheel, side view dimensions

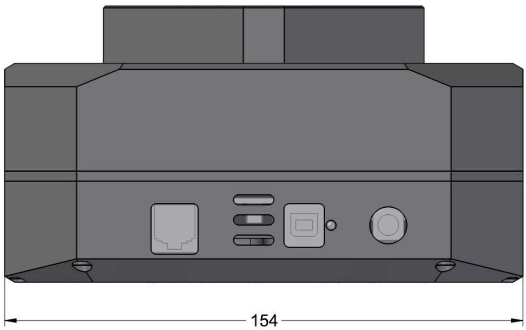


Figure 13: C4 camera head bottom view dimensions

Enhanced cooling variant

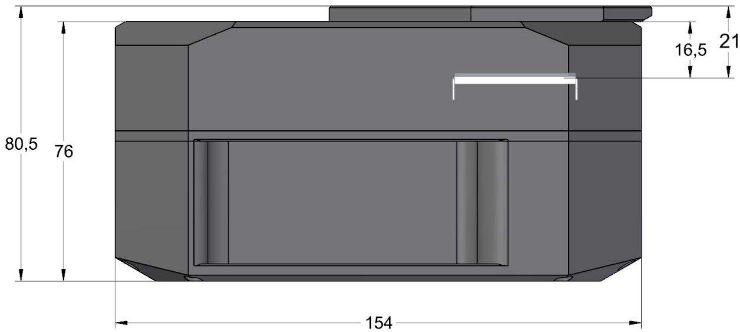


Figure 14: C4 camera head with Enhanced cooling side view dimensions

Camera with "L" External filter wheel

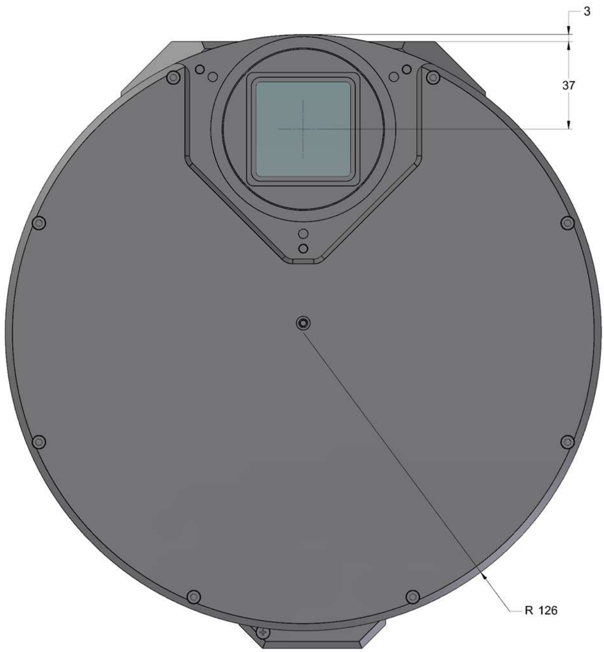


Figure 15: C4 camera head with External filter wheel front view dimensions

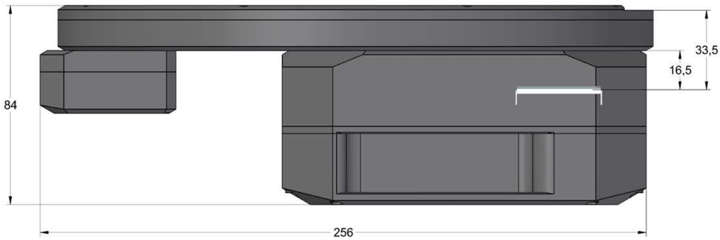


Figure 16: C4 camera head with External filter wheel side view dimensions

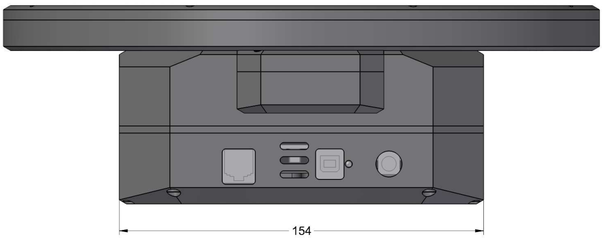


Figure 17: C4 camera head with External filter wheel bottom view dimensions

The “M” sized External Filter Wheel diameter is smaller (see External Filter Wheel User's Guide), but the back focal distance of all external filter wheels is identical.

Enhanced cooling with External filter wheel variant

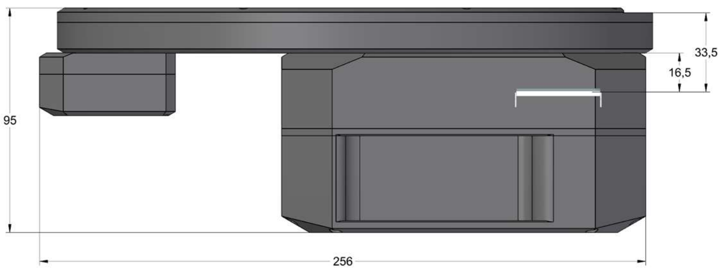


Figure 18: C4 camera head with Enhanced cooling and External filter wheel side view dimensions

Back focal distance

The stated back focal distances (BFD) include corrections for all optical elements in the light path (cold chamber optical window, sensor cover glass, ...), fixed in the camera body. So, stated values are not mechanical, but optical back focal distances. However, no corrections for filters are included, as the thicknesses of various filters are very different.

C4 cameras are manufactured in many variants and can be connected with various accessories, which leads to many possible back focal distance values.

There are two groups of the telescope and lens adapters, differing in back focal distance definition:

- Adapters **without strictly defined BFD**. These adapters are designed to provide as low BFD as possible.
- Adapter **with defined BFD**. These adapters are typically intended for optical correctors (field flatteners, coma correctors, ...) and also for photographic lenses. Keeping the defined BFD is necessary to ensure proper functionality of correctors or to be able to achieve focus with photographic lenses.

  If such adapter is to be used on the camera without filter wheel, it is necessary to use a thick adapter base with the same thickness like the External filter wheel to keep the BFD, for which the adapter is designed.

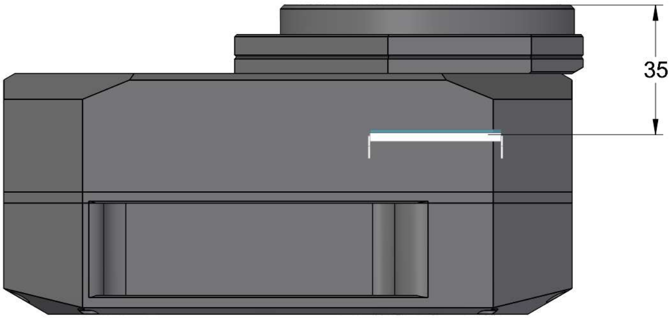


Figure 19: Back focal distance of the C4 camera without filter wheel and M68×1 threaded adapter on the thin adapter base

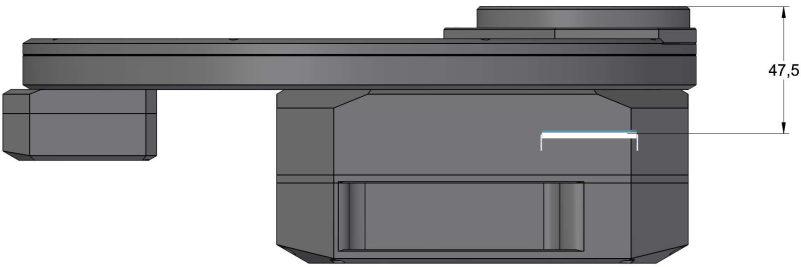
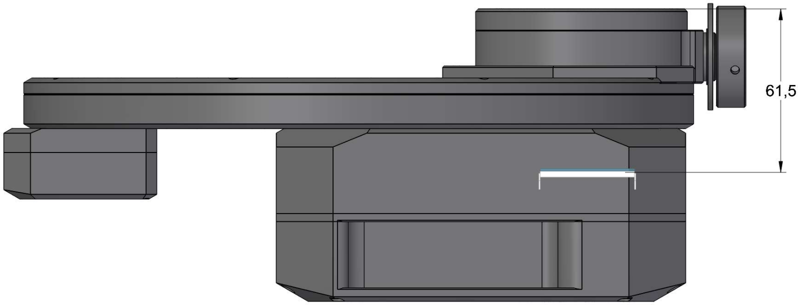


Figure 20: Back focal distance of the C4 camera with External filter wheel and M68×1 threaded adapter

Off-Axis Guider Adapter

The OAG for C4 cameras use M68×1 threaded adapter with 61.5 mm back focal distance.



Please note when the OAG has to be used with a camera without filter wheel, it is necessary to use a thick adapter base of the same thickness like the External filter wheel to keep the distance from OAG to sensor constant. Otherwise, the guiding camera cannot reach focus.

Optional accessories

Various accessories are offered with C4 cameras to enhance functionality and help camera integration into imaging setups.

Telescope adapters

Usage of many common types of telescope and lens adapters are ruled out by very large sensor used in C4 cameras. The sensor diagonal dimension of C4 cameras is 52 mm, which is greater than outer dimensions of many adapter kinds. Only the M68 threaded and Canon EOS bayonet adapters are large enough not to cause vignetting, Nikon lenses can be used in some special cases.

- **M68×1** – adapter with M68×1 **inner thread**.
- **Canon EOS bayonet** – standard Canon EOS lens adapter ("L" size). Adapter preserves 44 mm back focal distance.
- **Nikon bayonet** – standard Nikon lens adapter ("L" size). Adapter preserves 46.5 mm back focal distance.

All telescope/lens adapters of the C4 series of cameras can be slightly tilted. This feature is introduced to compensate for possible misalignments in perpendicularity of the telescope optical axis and sensor plane.

Adapters are attached either directly to the External filter wheel front plate or to the adjustable adapter base mounted on the camera head.

Off-Axis Guider Adapter (OAG)

C4 camera can be optionally equipped with Off-Axis Guider Adapter. This adapter contains flat mirror, tilted by 45° to the optical axis. This mirror reflects part of the incoming light into guider camera port. The mirror is located far enough from the optical axis not to block light coming to the main camera sensor, so the optics must be capable to create large enough field of view to illuminate the tilted mirror.

C4-OAG is manufactured with M68×1 thread with the back focal distance 61.5 mm.

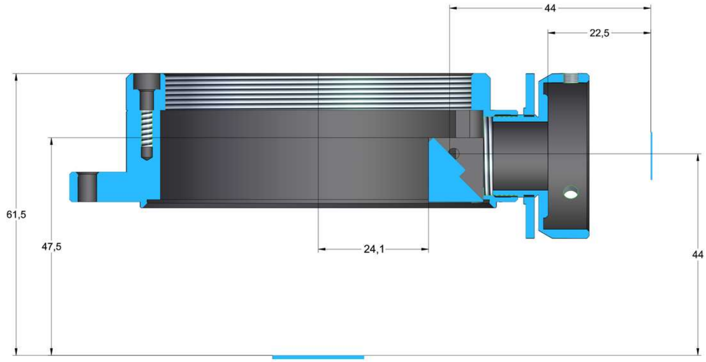


Figure 21: Position of the OAG reflection mirror relative to optical axis

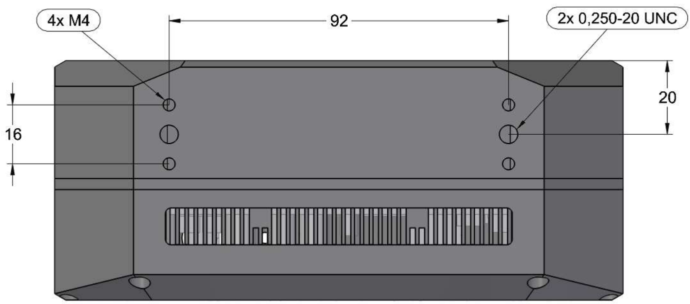
Figure 22: OAG on C4 camera with thick adapter base

If the OAG is used on camera without filter wheel, thicker adapter base must be used to keep the Back focal distance and to allow the guiding camera to reach focus.

OAG guider port is compatible with C1 cameras. It is necessary to replace the CS/1.25" adapter with short, 10 mm variant. Because C1 cameras follow CS-mount standard, (BFD 12.5 mm), any camera following this standard with 10 mm long 1.25" adapter should work properly with the C4-OAG.

Attaching camera head to telescope mount

C4 cameras are equipped with two "tripod" 0.250-20UNC threaded holes on the top side of the camera head, as well as four metric M4 threaded holes.



These threaded holes can be used to attach 1.75 inch "dovetail bar" (Vixen standard). It is then possible to attach the camera head, e.g. equipped with photographic lens, directly to various telescope mounts supporting this standard.

Figure 23: 1.75" bar for standard telescope mounts

Camera head color variants

Camera head is available in several color variants of the center plate. Visit manufacturer's web pages for current offering.

Figure 24: Camera color variants

Gx Camera Ethernet Adapter

Gx Camera Ethernet Adapter allows connection of up to 4 Gx cameras of any type on the one side and 1 Gbps Ethernet on the other side. This adapter allows access to connected Gx cameras using routable TCP/IP protocol over practically unlimited distance.

Figure 25: The Gx Camera Ethernet Adapter with two connected cameras

Adjusting of the telescope adapter

All telescope/lens adapters of the C4 series of cameras can be slightly tilted. This feature is introduced to compensate for possible misalignments in perpendicularity of the telescope optical axis and sensor plane.

Figure 26: Releasing of the "pushing" screw

The camera telescope adapters are attached using three "pulling" screws. As the adapter tilt is adjustable, another three "pushing" screws are intended to fix the adapter after some pulling screw is released to adjust the tilt.

> **Warning:**
>
> Both pulling and pushing screws, used on the C4 camera adapter, are fine-pitch M4×0.5 thread screws, not standard M4 thread ones. Always use only screws supplied with the adapter, using of normal M4 screws damages the adapter.

Because the necessity to adjust two screws (one pushing, one pulling) at once is inconvenient, the adapter tilting mechanism is also equipped with ring-shaped spring, which pushes the adapter out of the camera body. This means the pushing screws can be released and still slight releasing of the pulling screw means the distance between the adapter and the camera body increases. The spring is designed to be strong enough to push the camera head from the adapter (fixed on the telescope) regardless of the camera orientation.

When all three pulling screws are fully tightened, releasing of just one or two of these screws does not allow adapter to move, or at last only very slightly thanks to deformation of the adapter body. If the adapter has to be adjusted, it is necessary to slightly release all three pulling screws, which makes room for tilt adjustment.

Figure 27: Adjusting of the "pulling" screw

Only after the proper tilt is reached, the pushing screws should be slightly tightened to fix the adapter in the desired angle relative to camera head. This ensures long-time stability of the adjusted adapter.

Adjustable telescope/lens adapters are attached slightly differently depending if the adapter is attached directly to the camera head (e.g. when camera is equipped with internal filter wheel) or to the External filter wheel case.

- If the External filter wheel is used, the adapted base is not necessary, as the External filter wheel front plate is already designed to hold the spring and it also contains threads to fix respective adapters.
- C4 adapters are not mounted directly on the camera head. Instead, a tilting adapter base, holding the circular spring, is always used.

Figure 28: Off Axis Guider adapter on the adapter base, attached to the C4 camera without External filter wheel (left) and directly on the External filter wheel (right)

Camera Maintenance

The C4 camera is a precision optical and mechanical instrument, so it should be handled with care. Camera should be protected from moisture and dust. Always cover the telescope adapter when the camera is removed from the telescope or put the whole camera into protective plastic bag.

Desiccant exchange

The C4 camera cooling is designed to be resistant to humidity inside the sensor chamber. When the temperature decreases, the copper cold finger crosses freezing point earlier than the sensor chip itself, so the water vapor inside the sensor chamber freezes on the cold finger surface first. Although this mechanism works very reliably in majority of cases, it has some limitations, especially when the humidity level inside the sensor chamber is high or the chip is cooled to very low temperatures.

This is why a cylindrical container, filled with silica-gel desiccant, is placed inside the camera head. This cylindrical chamber is connected with the insulated cooled sensor chamber itself.

Warning:

High level of moisture inside the sensor cold chamber can cause camera malfunction or even damage to the sensor. Even if the frost does not create on the detector when the sensor is cooled below freezing point, the moisture can be still present. It is necessary to keep the sensor chamber interior dry by the regular exchange of the silica-gel desiccant. The frequency of necessary silica-gel exchanges depends on the camera usage. If the camera is used regularly, it is necessary to dry the sensor chamber every few months.

It is possible to dry the wet silica-gel by baking it in the oven (not the microwave one!) to dry it again. Dry the silica-gel for at last one or two hours at temperature between 120 and 140 °C.

The silica-gel used in C4 cameras changes its color according to amount of absorbed water – it is yellow-orange when it is dry and turns to green or transparent without any color hue when it becomes wet, depending on the silica-gel type (manufacturer). It is recommended to shorten replacement interval if the silica-gel is completely green or transparent upon replacement. If it is still yellow-orange, it is possible to prolong the replacement interval.

Figure 29: Silica-gel container is accessible from the camera back side

Exchanging the silica-gel

C4 cameras employ the same desiccant container like the C1+, C1x, C2 and C3 cameras. The whole container can be unscrewed, so it is possible to exchange silica-gel without the necessity to remove the camera from the telescope.

Silica-gel is held inside the container with a perforated cap. This cap is also screwed into the container body, so it is easy to exchange the silica-gel inside the container after it is worn out or damaged e.g. by too high temperature etc.

The container itself does not contain any sealing (the sealing remains attached to the sensor cold chamber inside the camera head), it consists of aluminum parts only. So, it is possible to heat the whole container to desired temperature without risking of the temperature-induced sealing damage.

Figure 30: Desiccant is held inside container by perforated cap

Note:

New containers have a thin O-ring close to the threaded edge of the container. This O-ring plays no role in sealing the sensor cold chamber itself. It is intended only to hold possible dust particles from entering the front half of the camera head with the sensor chamber optical window and shutter. While the O-ring material should sustain the high temperature during silica-gel baking, it is possible to remove it and put it back again prior to threading the contained back to the camera.

This design also allows usage of some optional parts:

- Threaded hermetic cap, which allows sealing of the dried container when it is not immediately attached to the camera head.
- Alternate (somewhat longer) desiccant container, modified to be able to be screw in and tightened (as well as released and screwed out) without any tool.

The sealing cap as well as the tool-less container are not supplied with the camera, they are supplied only as optional accessory.

Figure 31: Optional cap, standard and tool-less container variants for both standard cooling and enhanced cooling (prolonged) cameras

Desiccant containers for Standard cooling and Enhanced cooling cameras

The difference between Standard and Enhanced cooling cameras is the thickness of the camera back shell, containing heat sink. Naturally, the silica-gel container of Enhanced cooling variants must be longer. Otherwise, the containers are the same and the longer variant can be used with standard cooling cameras, it then only extends from the camera back.

Changing the Telescope Adapter

All adapters of the cameras are attached using three “pulling” screws. As the adapter tilt is adjustable, another three “pushing” screws are intended to fix the adapter in place.

If the adapter has to be replaced for another one, it is necessary to unscrew the three pulling screws. The adapter then can be removed and replaced with another one.

Warning:

Both pulling and pushing screws, used on the C4 camera adapter, are fine-pitch M4×0.5 thread screws, not standard M4 thread ones. Always use only screws supplied with the adapter, using of normal M4 screws damages the adapter.

Always make sure to carefully locate the ring-shaped spring prior to attaching the adapter.

Figure 32: Replacing of the adjustable telescope adapter

Power Supply Fuse

The power supply inside the camera is protected against connecting of inverted-polarity power plug or against connecting of too-high DC voltage (above 15 V) by electronic sensors. So, the camera just remains unpowered when wrong polarity or wrong voltage plug is connected.

Still, there is a fuse inside the camera head, adding one more layer of protection. If such event happens and the cooling fans on the back side of the camera do not work when the camera is connected to proper power supply (12 V DC, center + plug), return the camera to the service center for repair.

Dual-gain Camera Image Calibration

The GSENSE4040 sensors, used in the C4-16000 cameras, employ 12-bit ADCs (Analog to Digital Converters) only. However, there are two sets of ADCs inside the sensor, each capable to digitize the image with different gain – one set of ADCs uses low-gain channel, while the second set uses high-gain channel. Both 12-bit outputs are read in parallel for every exposure and can be combined into single image with true 16-bit dynamic range (such combined image is often called 16-bit HDR for High Dynamic Range).

16-bit HDR images, created from two 12-bit ones, are virtually indistinguishable from the true 16-bit ones. Differences between HDR combined image and true 16-bit image in both visual appearance (appreciated in aesthetic astro-photography) and information contents (important for research application) are beyond divergences caused by other sources.

But the fact, that every pixel of the resulting 16-bit HDR image originates either from high-gain frame of is a transformed low-gain frame pixel, poses a problem for proper image calibration. But let's start with algorithm used to combine low-gain and high-gain images into HDR one.

HDR image construction

Algorithm used to create a 16-bit HDR image is quite straightforward. The following steps are performed for every pixel:

1. If the **high-gain** image pixel **is less or equal** to a defined **threshold**, the high-gain pixel is moved to resulting image without any changes. The corresponding low-gain image pixel is not used, as the high-gain one has much better S/N ratio.
2. Else the high-gain image pixel is **above the threshold**, the **low-gain** image pixel is **transformed** to correspond to the high-gain image gain and offset and then it is put into resulting image. Transformation enlarges the low-gain pixel value from the 0 to 4095 range to full 0 to 65535 range. The corresponding high-gain image pixel is not used.

The algorithm written in pseudo-code would be:

```
for x = 0 to ImageWidth - 1 do
  for y = 0 to ImageDepth - 1 do
    if HiGainImage[ x, y ] <= Threshold then
      ResultImage[ x, y ] = HiGainImage[ x, y ];
    else
      ResultImage[ x, y ] = Transform( LoGainImage[ x, y ] );
    end;
  end;
end;
```

The value of **Threshold** is arbitrary set somewhere close to the upper limit of the 12-bit image dynamic range. C4-16000 drivers use Threshold equal to 3600. This sufficiently uses the perfectly linear portion of the high-gain image dynamic range (see the previous chapter). Values close to saturation signal, and thus slightly diverging from linear response curve, are cut off.

The **Transform** function coefficients slightly vary among individual sensors. The differences are rather minor, but every C4-16000 camera undergoes individual calibration and coefficients are stored into camera permanent memory. Driver performing the HDR combination reads these values from connected camera and uses them to perform HDR combination.

Advanced Calibration

The default 16-bit HDR read mode of the C4-16000 camera may lead some users to use this camera as any other camera with proper 16-bit conversion. Unfortunately, the fact that the 16-bit HDR image is combined from two independently digitized frames, causes such naïve approach cannot be used also for the image calibration. For instance, consider this:

- The dark frame signal is generated by dark current only, which is quite low (remember, the C4-16000 camera uses sensor cooling to significantly lower dark current). So, the dark frame pixels almost never cross the 3600 ADU threshold point. The result is that the 16-bit HDR dark frames virtually contain high-gain frame pixels only. But if the light image exceeds the 3600 ADU threshold, its pixels are transformed low-gain frame pixels. When subtracting 16-bit HDR dark frame from 16-bit HDR light image of some bright object, we in fact subtract high-gain dark frame from the transformed low-gain image pixels with entirely different dark current, different hot pixels etc.

- The common practice is to make flat fields reaching approximately a half of the sensor dynamic range, which is somewhere between 30000 and 35000 ADU for 16-bit image. All pixels of such 16-bit HDR flat field image are then transformed low-gain pixels, but typical astronomical image often contains many dim portions, remaining below the 3600 ADU threshold and thus taken from high-gain frame. Then we apply flat field created from low-gain frame to image containing majority of high-gain pixels with different response to light etc.

Note:

The fact, that the GSENSE4040 sensor consists of four quadrants, differing in bias value, dark current and response to light, makes the proper calibration crucially important to eliminate these differences.

Solution to the above-mentioned problems in calibration is rather simple in principle – it is necessary to use dark and flat field frames taken through high-gain channel when the light image pixels is below threshold and similarly, dark and flat field frames taken through low-gain channel, but transformed the same way like the light image pixel in the process of creating 16-bit HDR image, if its value is above the threshold.

So, **no dark frame nor flat field frame could be HDR combined (16-bit)**. It is necessary to create **two master dark frames**:

- The **first master dark** frame is acquired through high-gain channel. This dark frame will be used when the 16-bit HDR raw image pixels does not reach the threshold value.
- The **second master dark** frame is read using low-gain channel, but transformed the same way like the low-gain channel is transformed during HDR combination. This is why the C4-16000 camera driver offers read mode No.4 – **16-bit transformed Low-Gain**. This dark frame will be used when the 16-bit HDR raw image pixels value exceeds the threshold value.

Also, **two master flat field** frames are necessary:

- The **first master flat field** frame is acquired through high-gain channel.
- The **second master flat dark** frame is read using **16-bit transformed Low-Gain** read mode.

> Note:
>
> The 16-bit transformed Low-Gain read mode is marked simply as **LoGain "16b"** by the camera driver for space reasons. In fact, this is 12-bit Low-Gain mode, but all pixels are transformed to 16-bit dynamic range the same way like the Low-Gain channel is transformed in HDR image combination when the High-Gain pixel exceeds the Threshold limit. But in this case, there is no threshold limit and no High-Gain pixels are used, all Low-Gain are used and transformed to create this image.

Bias frames

First, let's emphasize that the still occasionally used method of dark frame calibration, including subtracting of bias frames from both dark and light images and only then subtracting of results, cannot be used with CMOS sensors, as these sensors actively adjust the "zero" offset to keep it on predefined values.

> Note:
>
> This is also the reason the methods used to measure the dark current of CCD sensors fail if applied to CMOS sensors, producing nonsense values.

Dividing the dark frame into "bias" and "dark – bias" frames was sometimes used to enable scaling of the "dark – bias" frame with exposure time. However, this method is only approximation as the dark current is influenced also by other factors than the reported sensor temperature, like the actual cooling performance, environment temperature affecting temperature gradients etc.

So, using biases during calibration in fact replaces the very simple operation:

Calibrated = Raw – Dark

With much more complex operation:

Calibrated = (Raw - Bias) - (Dark - Bias)
= Raw - Bias - Dark + Bias
= Raw - Dark

With exactly the same results.

Also, very important fact is that every additive operation increases the noise by square root of sum of squares of noise of both values.

$$\sigma_{result} = \sqrt{\sigma_{frame}^2 \ + \sigma_{fra}^2}$$

If both frames have the same noise, adding or subtracting them increases the noise by square root of two or approx. 1.41-times. So, naturally, the lowest number of such additive operations are used during calibration process the better.

The best way to perform dark frame calibration is to capture the set of dark frames at the same sensor temperature (ideally also at the same environment temperature) and with the same exposure time as the light frames and then to median-combine them into a master dark frame. The resulting master dark, is then subtracted from every light image with single additive operation. Both light image and master dark frame includes bias and the dark frame subtraction removes it from the light image together with the dark current. Leave bias frames for sensor performance evaluation etc., but completely avoid them during calibration process.

Note:

The same procedure should be applied when capturing flat fields. It is recommended to capture a set of dark frames, corresponding to a flat frame exposure time and at the same sensor temperature and then to median-combine them. Resulting master dark frame for flats should be subtracted from each flat image prior me median-combining them to master flat frame.

Naturally, the read mode used for respective flat field frames must be also used to capture also the corresponding dark frames.

SIPS Advanced Calibration tool

The SIPS (Scientific Image Processing System) package is a free software, shipped with every Moravian Instruments camera. It is possible to download SIPS from the Moravian Instruments web pages, too.

SIPS calibration tool was extended to support dual-dark and dual-flat calibration for C4-16000 camera.

Note:

The functionality described here is fully implemented in the **SIPS version 3.31** and higher.

If using the **ASCOM driver**, required read mode No. 4 (**LoGain "16b"** – 16-bit transformed low-gain) is available in driver **version 5.6** and higher.

High-Gain master dark frame

The C4-16000 camera should be switched to **HiGain 12b** read mode. Capture a set of dark frames of the same exposure time like the light images. Take care to:

- If multiple exposure times are used for light images, multiple dark frame sets should be captured, one set for each used exposure time.
- Ideally, the environment temperature should be the same or at last similar to the environment temperature during imaging due to temperature gradients affecting the actual sensor temperature.
- Leave the temperature to settle for 5 or 10 minutes prior to capturing dark frames, do not start immediately when the camera indicates the target temperature was reached.
- Do not capture dark frames immediately after flat of light frames. The GSENSE4040 sensor used in C4-16000 suffers from Residual

Bulk Image effect. Let the sensor several tens of minutes to dissipate RBI before you capture dark frames.

Individual frames should be median combined into master dark frame. Using median combination eliminates radiation spikes and other artifacts in master dark image.

If using SIPS **Math and Filters** to perform median combination, uncheck the **Level mean values of all images** check-box. This option is included to compensate different mean values of individual frames e.g. when taking flat fields on sky during twilight or dawn, when the sky brightens changes among exposures.

Low-Gain 16b master dark frame

The C4-16000 camera should be switched to **LoGain "16b"** read mode. As opposed to **LoGain 12b** mode, the 16-bit variant performs the HDR transformation with every pixel of the image, expanding the 12-bit dynamic range to 16-bits. Beside the read mode, the procedure is the same like in the case of High-Gain master dark frame.

High-Gain master flat field

Capture a set flat field image with C4-16000 camera using **HiGain 12b** read mode. Corresponding dark frames, used to create master dark frame for this flat, should be captured in the same read mode.

If the flat field images are captured on the sky and a master flat field median combination is performed using SIPS **Math and Filters**, check the **Level mean values of all images** check-box. This option compensates different mean values of individual frames, caused by changing sky brightens among exposures.

As the used read mode is 12-bit, so the mean value of acquired frames should be **between 2000 and 2500 ADU**.

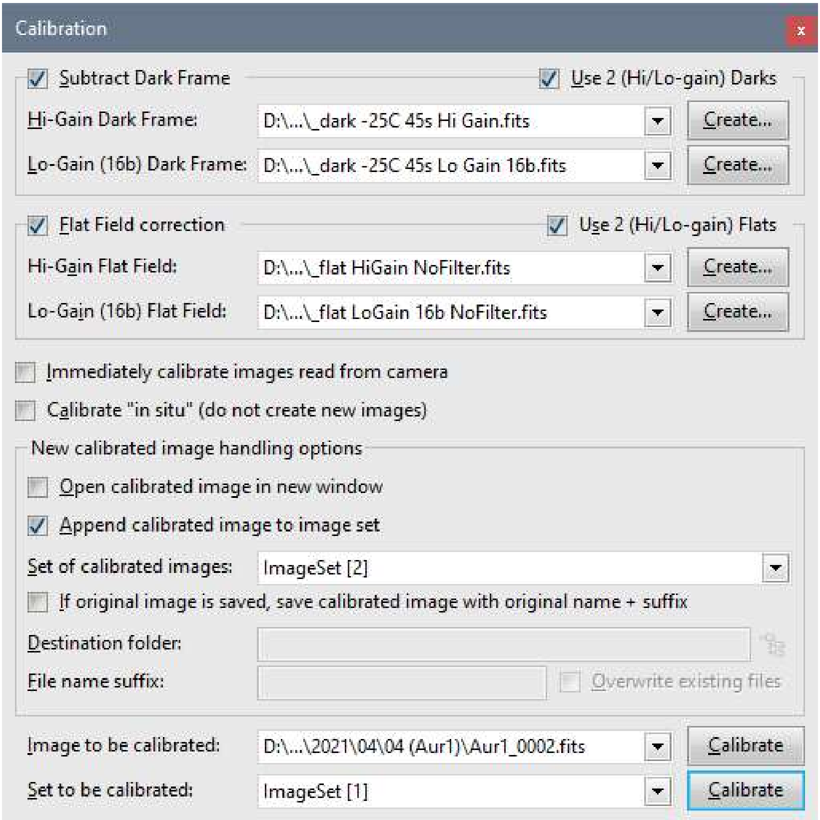
Low-Gain 16b master flat field

As in the case of Low-Gain 16-bit master dark frames, the C4-16000 camera should be switched to **LoGain "16b"** read mode, which is of course true also for corresponding dark frames.

While the low-gain frame is also 12-bit only, the used **LoGain “16b”** read mode transforms every pixel into 16-bit dynamic range. So, the mean value of acquired frames should be **around 33000 ADU**.

SIPS Calibration tool

When all 4 calibration frames are ready, calibration of any 16-bit HDR raw image or image set can be performed using the SIPS **Calibration** tool.



Note:

The calibration of dual-gain cameras should always be performed at once. When calibrating single-gain raw images, regardless if 12 or 16-

bit deep, it is possible to subtract dark frame from raw images and to apply flat field to these intermediate images anytime later.

But as described above, the advanced calibration of dual-gain camera depends on testing of the threshold. But subtracting of the dark frame actually lowers the pixel value. So, even pixels created by transformation of the low-gain ones during HDR combination, may be below the threshold value after dark frame subtraction. This would lead to using of high-gain flat field instead of transformed low-gain one.

So, if both dark frame and flat field calibration are to be performed on 16-bit HDR raw frames, always perform the calibration in one step. SIPS calibration code handles this situation correctly.

To perform advanced calibration, simply check respective check-boxes **Use 2 (Hi/Lo-gain) Darks** and **Use 2 (Hi/Lo-gain) Flats**. Then select respective calibration frames and choose other options in the SIPS Calibration tool the same way like in the case of standard calibration.

Example calibration frames

The sample calibration frames, showed below, clearly demonstrate differences in individual quadrants of the GSENSE4040 sensor.

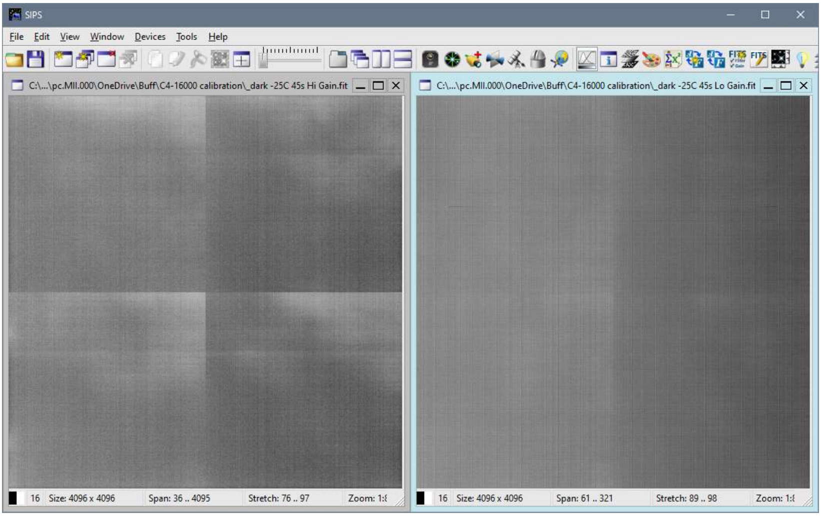


Figure 33: Example high gain (left) and low-gain(right) dark frames

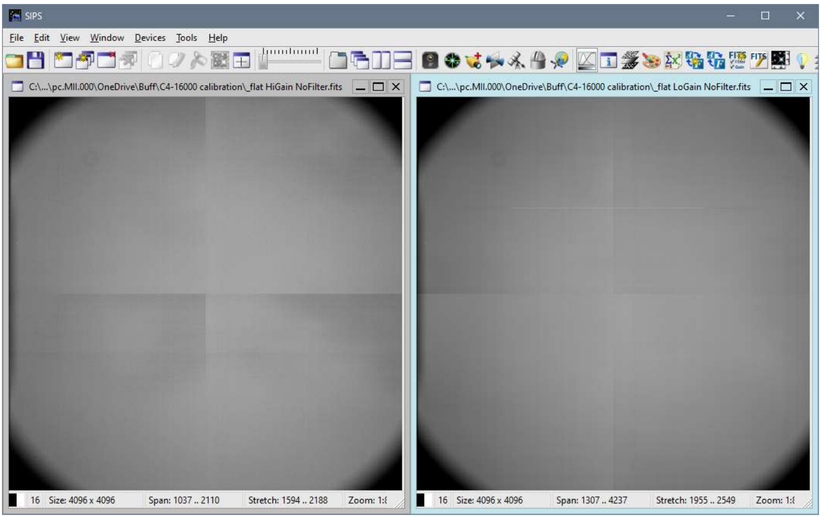


Figure 34: Example high gain (left) and low-gain(right) flat field frames

The raw and calibrated image example blow are only cropped section around image center of real series of 45s long exposures of a star field.

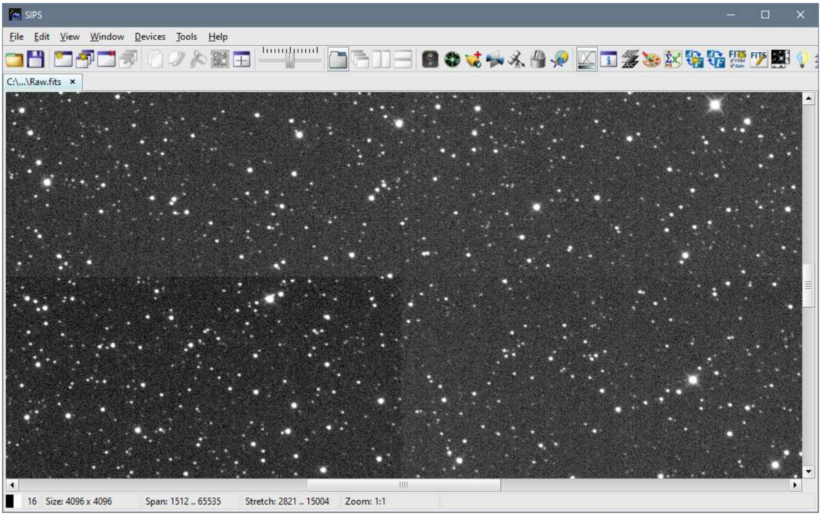


Figure 35: Single highly stretched 16-bit HDR raw image shows non-uniform response of GSENSE4040 sensor

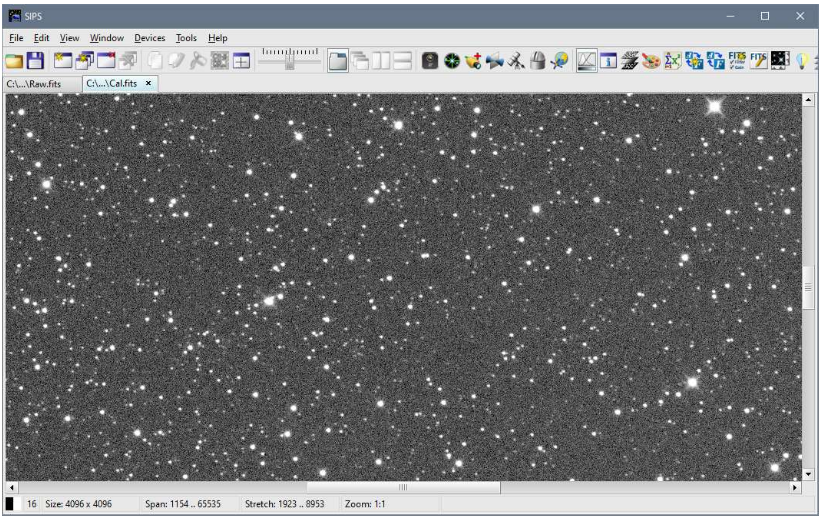


Figure 36: Single highly stretched 16-bit HDR image, calibrated using the SIPS Advanced Calibration tool with four calibration frames, virtually eliminates any traces of the GSENSE4040 non-uniformity

Conclusion

The advanced calibration can significantly eliminate the influence of GSENSE4040 dual-gain nature as well as its quad-pattern structure leading to non-uniform image background.

But despite all effort, results of advanced calibration may vary depending on many factors. Especially on sums of large number of images, which effectively increases the S/N ratio and lowers the background noise, the GSENSE4040 quad pattern may remain visible. This also depends on image stretching, but also on the monitor used to observe images etc. In such cases, other techniques like dithering during image capturing may help to eliminate any remaining artifacts.

It is worth noting that even if the remaining background non-uniformity can be visually detected on very stretched images, it is very low compared to accumulated signal. So, it is purely aesthetic issue and many orders of magnitude below other sources of errors, affecting scientific applications. So, for research applications, the dual-gain sensors and 16-bit HDR combination bring no barriers in using of C4-16000 camera.