C5 Series

Astronomical Cameras

User’s Guide

Version 1.8

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C5 cameras are not authorized for and should not be used within Life Support Systems without the specific written consent of the Moravian Instruments. Product warranty is limited to repair or replacement of defective components and does not cover injury or property or other consequential damages.

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Introduction

Thank you for choosing the Moravian Instruments camera. The C5 series of cooled scientific CMOS cameras were developed for imaging under extremely low-light conditions in astronomy, microscopy, and similar areas.

C5 camera series is designed to accommodate the latest generation of the extremely large Sony IMX CMOS sensors with 100 and 150 MPx resolution and diagonal dimension up to 67 mm. These sensors belong to the same family as the sensors used in the C3 camera series, sharing the same 3.76 µm pixel size with the full-well capacity exceeding 50 ke^-, very high quantum efficiency thanks to back-illuminated design and very low dark current. C5 sensors also offer 16-bit digitization, perfectly linear response to light and exceptionally low read noise.

Despite very large sensors, the C5 camera head dimensions are the same like the Enhanced Cooling variants of the C3 and C4 series. All these features make C5 cameras the ultimate devices for both aesthetic astro-photography as well as astronomical research.

Rich software and driver support allow usage of C5 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 C5 camera with broad variety of camera control programs.

The C5 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.

C5 cameras are designed to be attached to host PC through very fast USB 3.0 port. While the C5 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 C5, but also other models from C0 to C4) 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 camera must be connected to some optical system to capture images. As the C5 cameras offer really large sensors with diagonals of 67 mm (150 MPx version) and 55 mm (100 MPx version), optical system must be capable to cover such large field of view. 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.

C5 cameras are made in two versions:

- Asymmetrical version marked C5A
- Symmetrical version marked C5S

Asymmetrical C5A variant look reveals the same time-proven design school of the C3 and C4 series in both outer shape and internal construction. C5A camera head front cross-section is the same like the in the case of C3 and C4 series, although the used sensors are much larger. C5 head thickness corresponds to the thickness of the Enhanced Cooling versions of the earlier models.

Figure 1: Asymmetrical C5A camera head

Asymmetrical models also employ mechanical shutter, allowing to capture dark or bias frames without a necessity to cover the telescope aperture.

Symmetrical C5S variant main purpose is not to exceed the central obstruction of reflecting telescopes with the camera located in the primary focus. The asymmetrical variant typically overhangs the central obstruction of smaller telescopes (with ~0.4 m primary mirror diameter), despite the central obstruction of wide-field telescope is rather big.

Figure 2: Symmetrical C5S camera head

Due to mechanical constrains, the symmetrical model lacks the mechanical shutter.

Asymmetrical and symmetrical model comparison:

Feature	Asymmetrical C5A	Symmetrical C5S
100 and 150 MPx sensors	Yes	Yes
Compatibility with filter wheels	Yes	Yes
M68 and M85 tiltable adapters	Yes	Yes
Mechanical shutter	Yes	No
Optional GPS receiver	Yes	Yes
Hardware trigger input	No	Yes

Figure 3: C5S (left) and C5A (right) camera models

Both C5A and C5S series feature completely redesigned air cooling – more powerful and also quieter than even the EC variants of the C3 and C4. Also, the supplied AC/DC brick power adapter is more powerful and employs more robust power plug.

C5 Camera Overview

C5 camera head is designed to be used with or without external filter wheel. The EFW-5XL external filter wheel, designed especially for the C5 cameras, can accommodate 5 square 65×65 mm filters, which are big enough even for the C5A-150M camera model. Another option is 7 filter positions for 50×50 mm filters, but this variant is suitable only for the C5A-100M camera with smaller sensor.

Figure 4: C5A camera with M85×1 adapter (left), C5 with EFW and M68×1 adapter (center) and C5 with EFW and M85×1 adapter (right)

C5 cameras can be shipped with either M85×1 or with smaller M68×1 threaded adapters. Again, the smaller M68×1 adapter is intended for C5A-100M cameras only.

Adjustable adapters are mounted on the adapter base attached to the C5 camera head. If the filter wheel is used, it is attached directly to the C5 camera head and the adjustable adapter base is manufactured directly on the filter wheel front plate.

Both C5A and C5S cameras can be optionally equipped with a GPS receiver, mounted on the camera back side close to the power and USB connectors.

GPS receiver provides geographic location, but especially precise timing of exposures. Individual exposures can be tagged with GPS time up to µs resolution.

The symmetrical C5S models are also equipped with a hardware trigger input, allowing starting of exposures by external hardware and thus precise synchronization of exposures of multiple cameras etc.

C5 Camera System

Components of C5 Camera system include:

1. C5A or C5S camera head
2. External Filter Wheel "XL" size
3. 7-positions filter wheel for "XL" housing for 50 × 50 mm square filters

> The 50×50 mm filters are useable with C5A-100M camera, which sensor longer side measures 44 mm. C5A-150M camera sensor longer side measures 53.4 mm, so 48×48 mm clear openings in the filter wheel partially cover sensor sides.

4. 5-positions filter wheel for "XL" housing for 65 × 65 mm square filters
5. Canon EOS bayonet adapter for the "XL" size External Filter Wheel with 44 mm BFD
6. M68 × 1 threaded adapter, BFD is 35 mm when mounted directly on camera head and 47.5 mm when mounted on EFW

> The M68×1 adapter is suitable for C5A-100M camera with smaller sensor, the C5A-150M version should use greater M85×1 adapter not to cause vignetting.

7. M85 × 1 threaded adapter, BFD is 31 mm when mounted directly on camera head and 43.5 mm when mounted on EFW
8. C5-OAG (Off-Axis Guider Adapter) with M85 × 1 thread for the "XL" size External Filter Wheel with 61.5 mm BFD
9. 10 mm long CS-to-1.25" adapter, used to attach CS-mount (C-thread, 12.5 mm BFD) compatible guider cameras to the OAG
10. C1 or C0 guider camera

Note the mechanical constrains of the C5S camera do not allow usage of the C1 camera, only the smaller C0 cameras can be used with C5S models.

C0 and 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.

11. Moravian Camera Ethernet Adapter (x86 CPU)
12. Moravian Camera Ethernet Adapter (ARM CPU)

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

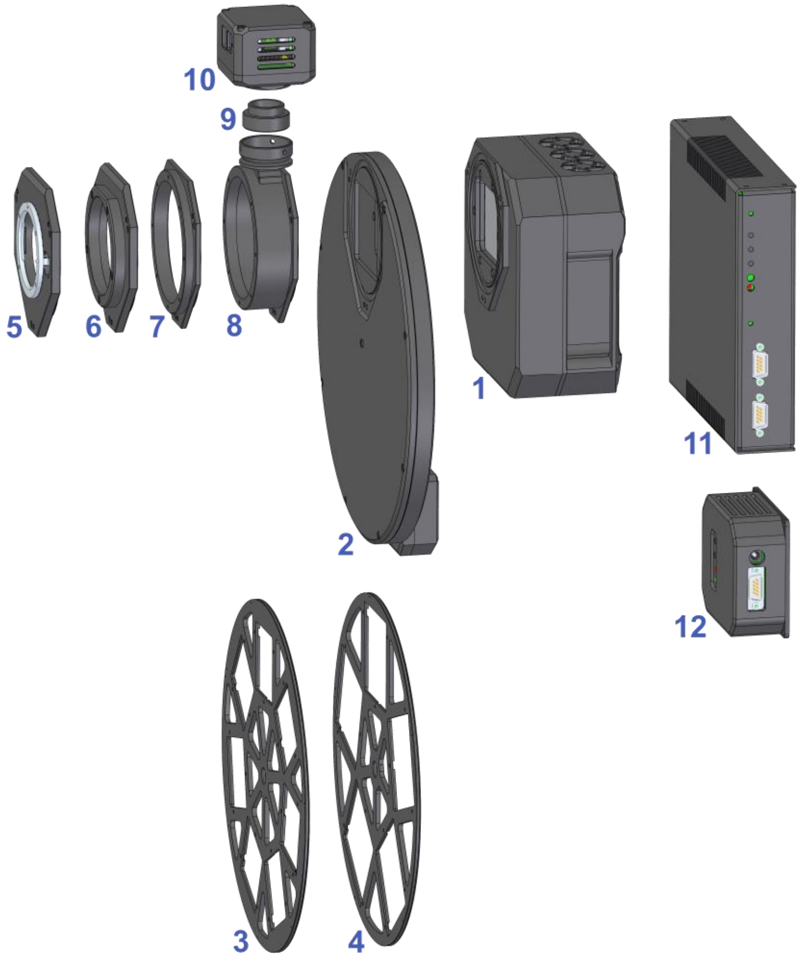


Figure 5: Schematic diagram of the C5A camera system components

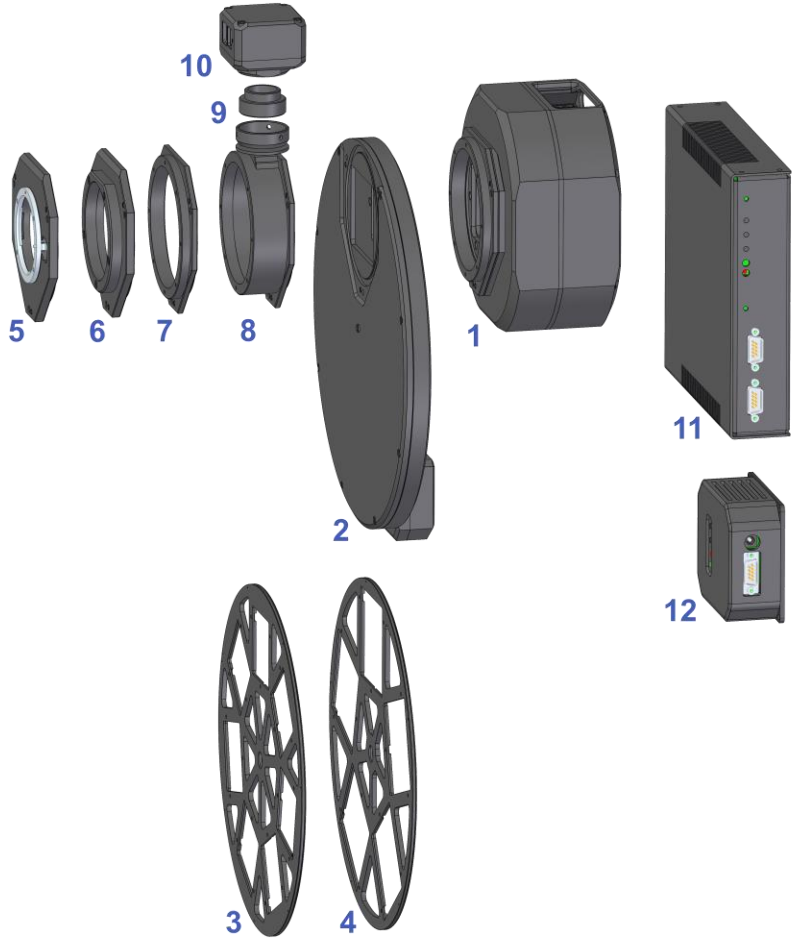


Figure 6: Schematic diagram of the C5S camera system components

CMOS Sensor and Camera Electronics

Both C5A and C5S cameras are equipped with Sony IMX rolling shutter **back-illuminated** CMOS detectors with 3.76 × 3.76 µm square pixels. Despite the relatively small pixel size, the full-well capacity over 50 ke- rivals the full-well capacity of competing CMOS sensors with much greater pixels and even exceeds the full-well capacity od CCD sensors with comparable pixel size.

The used Sony sensors are equipped with 16-bit ADCs (Analog to Digital Converters). 16-bit digitization ensures enough resolution to completely cover the sensor exceptional dynamic range.

> While the used sensors offer also lower dynamic resolution (12 and 14 bit), C5 cameras do no utilize these modes. Astronomical images always use 2 bytes for a pixel, so lowering the dynamic resolution to 14 or 12 bits brings no advantage beside the slightly faster download. But cooled astronomical cameras are intended for very long exposures and a fraction of second saved on image download is negligible compared to huge benefits of 16-bit digitization.

C5 camera models include:

Model	C5A/S-100M	C5A/S-150M
CMOS sensor	IMX461	IMX411
Color mask	None	None
Resolution	11664 × 8750 pixels	14208 × 10656 pixels
Pixel size	3.76 × 3.76 µm	3.76 × 3.76 µm
Sensor size	43.86 × 32.90 mm	53.42 × 40.07 mm

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 C5 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.

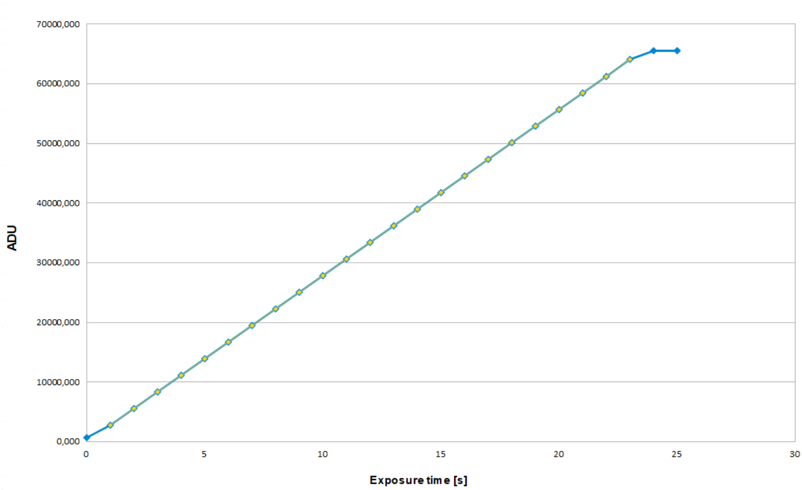


Figure 7: IMX461 sensor response to light

Download speed

C5 cameras are equipped with on-board RAM, capable to hold several 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 digitize and download single full frame depends on USB connection type.

Camera model	C5A-100M	C5A-150M
Full-frame, USB 3.0 (5 Gbps)	0.66 s	0.95 s
Full-frame, USB 2.0 (480 Mbps)	5.57 s	6.80 s

If only a sub-frame is read, time needed to digitize and download image is naturally lower. However, the download time is not cut proportionally to number of pixels thanks to some fixed overhead time, independent on the sub-frame dimensions.

Camera model	C5A-100M	C5A-150M
1024×1024 sub-frame, USB 3.0 (5 Gbps)	0.05 s	0.05 s
1024×1024 sub-frame, USB 2.0 (480 Mbps)	0.07 s	0.07 s

The driver is sometimes forced to read bigger portions of the sensor than the user defined because of a sub-frame position and dimension limitations imposed by the sensor hardware. Sometimes it is even necessary to read a whole sensor.

It is recommended to click the **Adjust Frame** button in the **Frame** tab of the SIPS camera control tool. The selected frame dimensions are then adjusted according to sensor limitations. Adjusted frame is then read from the sensor, without a necessity to read a bigger portions or even whole sensor and crop image in firmware.

C5 camera electronics supports in-camera 2×2 binning. If this binning mode is used, download speed increases because of less amount of data read from camera.

Camera model	C5A-100M	C5A-150M
Full-frame 2×2 binning, USB 3.0 (5 Gbps)	0.43 s	0.60 s
Full-frame 2×2 binning, USB 2.0 (480 Mbps)	1.15 s	1.71 s

Download speed when using the Moravian Camera Ethernet Adapter depends if the 100 Mbps or 1 Gbps Ethernet is used, if USB 2 or USB 3 is used to connect camera to Ethernet Adapter device, but also depends on the particular network utilization etc.

When the camera is connected to the Ethernet Adapter using USB 3 and 1 Gbps Ethernet is directly connected to the host PC, download time of the C5-100M full frame is approx. 3.5 s.

Camera gain

Sensors used in C5 cameras offer programmable gain from 0 to 36 dB, which translates to the output signal multiplication from 1× to 63×.

Note the C5 camera firmware supports only **analog gain**, which means real amplification of the signal prior to its digitization. The used sensors support also **digital gain** control, which is only numerical operation, bringing no real benefit for astronomical camera. Any such operation can be performed later during image processing if desired.

Camera driver accepts gain as a number in the range 0 to 4030, which corresponds directly to sensor's register value. This number does not represent gain in dB nor in multiply value. However, the driver offers a function, which transforms the gain numerical value to gain expressed in dB as well as multiply. Some selected values are shown in the table:

Gain number	Gain in dB	Gain multiply
0	0.00	1.00×
500	1.13	1.14×
1000	2.43	1.32×
1500	3.96	1.58×
2000	5.82	1.95×
2500	8.19	2.57×
3000	11.46	3.74×
3500	16.75	6.88×
4000	32.69	43.11×
4030	35.99	63.00×

Conversion factors and read noise

Generally, many sensor characteristics depend on the used gain. Also, the used sensors employ two conversion paths. One path offers very low read noise, but cannot utilize full sensor dynamic range. Another conversion path offers maximum pixel capacity, but at the price of higher read noise. The cross point is set to gain 3× (approx. 10dB), where the full well capacity drops from more than 50 ke- to ~17 ke-. The read noise then drops from ~3.2 e- RMS to ~1.5 e- RMS.

Gain number	0	2749	2750	4030
Sensor gain	0.0 dB	9.7 dB	9.7 dB	36 dB
	1×	3×	3×	63×
Full well capacity	50000 e-	16500 e-	16500 e-	11200 e-
Conversion factor	0.76 e-/ADU	0.25 e-/ADU	0.25 e-/ADU	0.17 e-/ADU
Read noise	3.52 e- RMS	3.13 e- RMS	1.51 e- RMS	1.44 e- RMS

Sensor dynamic range, defined as full well capacity divided by read noise, is greatest when using gain 0, despite somewhat higher read noise:

- At gain = 0, dynamic range is 50000 / 3.52 = 14205×
- At gain = 2750, dynamic range is 16500 / 1.51 = 10927×

Also, it is worth noting that in reality the noise floor is only rarely defined by read noise. Unless the camera is used with very narrow narrow-band filter (with FWHM only a few nm) and under very dark sky, the dominant source of noise is the sky glow. When the noise generated by sky glow exceeds approximately 4 e- RMS, extremely low read noise associated with gain set to 2750 or more is not utilized and dynamic range is unnecessarily limited by the lowered full well capacity.

So, which gain settings is the best? This depends on the particular task.

- Gain set to 2750 can be utilized when imaging through narrow-band filter with appropriately short exposures, so the background noise does not exceed the read noise. This is typical for aesthetic astro-photography, where the lowered full well capacity does not negatively influence the result quality.
  But even without narrow-band filters, the extremely low read noise allows stacking of many short exposures without unacceptable increase of the stacked image background noise, caused by accumulation of high read noise of individual exposures.
- Gain set to 0 offers maximum full well capacity and the greatest sensor dynamic range, which is appreciated mainly in research applications. Pass-bands of filters used for photometry are relatively wide and sky glow is the dominant source of noise.
  But also, for RGB images, used for aesthetic astro-photography, higher dynamic range allows longer exposures while the bright portions of the nebulae and galaxies still remain under saturation limit and thus can be properly processed.

Please note the values stated above are not published by sensor manufacturer, but 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.

Binning

The camera driver and user's applications offer wide variety of binning modes up to 4×4 pixels as well as all combinations of asymmetrical binning modes 1×2, 1×3, 1×4, 2×4 etc. To allow such flexibility, binning is performed only in the camera driver (software binning) and does not rely on the limited capabilities of the hardware binning.

The negative side of software binning is the same download time like in the case of full-resolution 1×1 mode. For typical astronomy usage, the small fraction of second download time is irrelevant, but for applications sensitive to download time, the hardware 2×2 binning can be useful.

Hardware binning

The C5 camera implements 2×2 binning mode in hardware in addition to normal 1×1 binning. This mode can be turned on and off using the **HWBinning** 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, the in-camera hardware binning is used and software binning is no longer available. 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.

Adding vs. averaging pixels

The traditional meaning of pixel binning implies adding of binned pixels. This originated in CCD sensors, where pixel charges were literally poured together within the sensor horizontal register and/or the output node.

For CMOS sensors with full 16-bit dynamic resolution, the negative side of binning is limiting of the sensor dynamic range, as for instance only ¼ of maximum charge in each of the 2×2 binned pixels leads to saturation of resulting pixel. CCDs eliminated this effect to some extend by increasing of the charge capacity of the output node and also by decreasing of the conversion factor in binned modes. But such possibilities are not available in CMOS detectors.

CMOS sensors with less than 16-bit precision often just add binned pixels to fulfil the available resolution of 16-bit pixels. For instance, camera with 12-bit dynamic range can sum up to 4×4 pixels and still the resulting binned pixels will not overflow the 16-bit range.

In theory, the resulting S/N ratio of binned pixel remains the same regardless if we add or average them. Let's take for example 2×2 binning:

- If we add 4 pixels, signal increases 4-times and noise increases 2-times – three additive operations increase noise by $\sqrt{(\sqrt{2})^2 \times (\sqrt{2})^2}$. Resulting S/N increases 2-times, but only until the sum of all pixels is lower than the pixel capacity.
- If we average 4 pixels, signal remains the same but the noise is lowered to ½ as noise is also averaged $\frac{\sqrt{(\sqrt{2})^2 \times (\sqrt{2})^2}}{4}$. Resulting S/N also increases 2-times, but only until the noise decreases to lowest possible 1-bit of dynamic range.

As the C5 camera read noise in the maximum dynamic range (gain 0) is around 3.5 ADU, halving it in 2×2 binning mode still keeps the read noise above the lower 1-bit limit and at the same time binned pixel will not saturate. For higher binning modes, the noise approaches lower limit, but averaging pixels still protects from pixel saturation, which is more important than possible S/N limitation caused by underflow of read noise.

If we take into account that the image background noise is only rarely defined by the read noise of the sensor, as the noise caused by background sky glow is typically much higher, for 16-bit camera averaging pixels is definitely the better way to bin pixels compared to just adding them. This is why both software and hardware binning modes in the C5 cameras are by default implemented as averaging of pixels, not summing.

However, both software and hardware binning modes can be switched to sum binned pixels instead of average them by the **BinningSum** parameter in the 'cXusb.ini' configuration file:

```
[driver]
BinningSum = true
```

Let's note there is one more possibility to bin pixels – in the application software. This time binning is not performed in camera hardware nor in the camera driver. Full resolution 1×1 image is downloaded from the camera and software itself then performs binning. The SIPS software adds pixels instead of averaging them, but at the same time SIPS converts images from 16-bit to 32-bit dynamic range. This means S/N of the binned images always increases, pixels never saturate and read noise newer approaches lower limit. The negative side of this option is two-time bigger images.

Binning in photometry

Saturated pixels within bright stars are no issue for aesthetic astro-photography, but photometry measurement is invalid if any pixel within the measured object reaches maximum value, because it is not possible to determine the amount of lost flux. Software performing photometry (e.g. the SIPS Photometry tool) should detect saturation value and invalidate entire photometric point not to introduce errors.

But binning efficiently obliterates the fact that any of the binned pixels saturated (except for all binned pixels reached saturation value). So, using of binning modes for research applications (photometry and astrometry) can lead to errors caused by lost flux in saturated pixels, which cannot be detected by the processing software due to binning.

This is why the behavior of both software and hardware binning modes is user-configurable through the **BinningSaturate** parameter in the 'cXusb.ini' configuration file:

```
[driver]
BinningSaturate = true
```

If the **BinningSaturate** parameter is set to true, resulting binned pixel is set to saturation value if any of the source pixels is saturated. For aesthetic astro-photography, keeping this parameter false could result into slightly better representation of bright star images, but for research applications, this parameter should always be set to true.

Exposure control

The shortest theoretical exposure time of the C5 cameras depends on the used sensor type:

- C5-100M shortest exposure is 164 μs
- C5-150M shortest exposure is 183 μs

However, such short exposures have no practical application, especially in astronomy. The camera firmware rounds exposure time to a multiply of 100 μs intervals, so in reality the shortest exposure time of both camera models is 200 μs.

> Note the individual lines are not exposed at the same time, regardless of how short the exposure is, because of the rolling-shutter nature of the used sensors. The difference between the first and last line exposure start time is 0.49 s for the C5-150M and 0.36 s for the C5-100M camera.

There is no theoretical 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).

> Please note the short exposure timing is properly handled in the camera firmware version 6.7 and later.

C5A mechanical shutter

C5A 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 etc.

Mechanical shutter in the C5A 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.

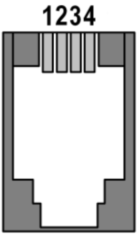
Camera firmware optimizes the shutter operation to avoid unnecessary movements. If a series of light images is taken immediately one after another, the shutter remains open not to introduce quite significant delay of the close/open cycle between each pair of subsequent light images. In the case next image is a 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 approx. 10 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.

C5S hardware trigger input

The C5S camera trigger input allows for external hardware to determine the exact time of exposure start.

> The external exposure triggering is supported by a variant of the **StartExposure** function named **StartExposureTrigger**, available for the user of the Camera SDK for Windows as well as Linux and Mac libraries and drivers. However, the SIPS software does not support triggered exposures.

The trigger input port uses the RJ11 four-pin connector. Pins 1 and 2 are connected and have a function of positive pole, pins 3 and 4 are connected to negative pole. The trigger is activated when an external hardware connects pins 1 and/or 2 with pins 3 and/or 4. The trigger input port is electrically isolated from the rest of the camera – power and USB grounds etc.



Pin	Function
1	Positive (+) pin No. 1
2	Positive (+) pin No. 2
3	Negative (-) pin No. 1
4	Negative (-) pin No. 2

The trigger input is located on the upper-left portion of the C5S camera back side, just above the power input plug.

Figure 8: Back side of the C5S (left) and C5A (right) cameras

GPS exposure timing

Both C5A and C5S cameras can be equipped with GPS receiver module (see the Optional Accessories chapter). The primary purpose of the GPS receiver is to provide precise times of exposures taken with the camera, which is required by applications dealing with astrometry of fast-moving objects (fast moving asteroids, satellites, and space debris on Earth orbit, …).

The GPS module needs to locate at last 5 satellites to provide exposure timing information. Geographic data are available if only 3 satellites are visible, but especially the mean sea level precision suffers if less than 4 satellites are used.

The camera SDK provides functions, allowing users to access precision exposure times as well as geographics location. The SIPS software package main imaging camera control tool window contains the GPS tab, which shows the state of the GPS fix.

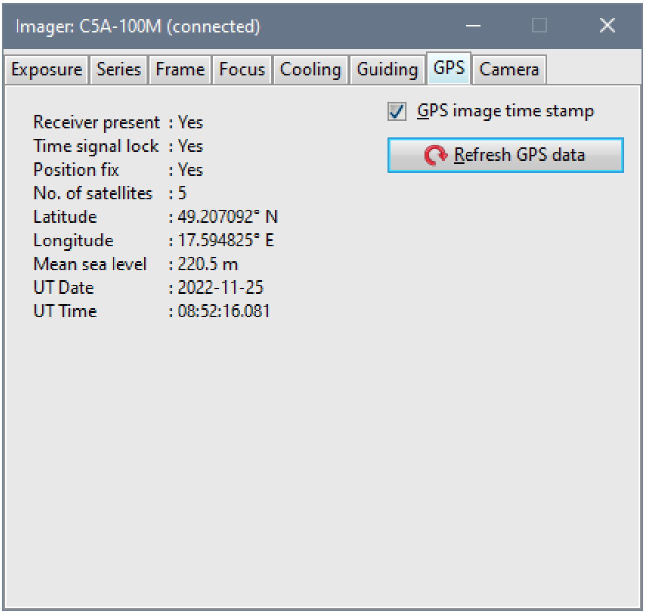


Figure 9: SIPS offers GUI to determine the state the GPS receiver

Determination of exact exposure time is quite complicated because of the rolling-shutter nature of the used sensors. Camera driver does all the calculations and returns the time of the start of exposure of the first line of the image. Still, users interested in precise exposure timing need to include several corrections into their calculations:

1. Individual image lines are exposed sequentially. The time difference between start of exposure of two subsequent lines is fixed for every sensor type:

i. C5-100M line exposure takes 40.944 µs
ii. C5-150M line exposure takes 45.833 µs

2. If the image is binned, single line of resulting image contains signal from multiple added (or averaged) lines, each with different exposure time start. The exposure start of individual lines of the binned images differs by the single line time difference, multiplied by the vertical binning factor.
3. If only a sub-frame is read, it must be considered that the sensor imposes some restrictions to the sub-frame coordinates. If the required sub-frame coordinates violate the sensor-imposed rules, camera driver enlarges the sub-frame region to fully contain desired sub-frame and then crops it by software. The provided start exposure time then concerns the first line actually read from the camera, not the first line of the resulting (software cropped) image.
   For instance, the y-coordinate of the sub-frame must not be lower than 25 lines. If a sub-frame with lower y-coordinate is asked by the user, whole frame is read and cropped by software.
   Note the camera SDK offers function **AdjustSubFrame**, which returns the smallest sub-frame, fully containing the requested sub-frame, but also fulfilling the sensor-imposed sub-frame coordinate restriction. If adjusted sub-frame is read, no software cropping occurs and image exposure time concerns the first line of the image. The SIPS software offers the “Adjust Frame” button, which adjusts actually defined sub-frame.

Please note the precise exposure timing is properly handled in the camera firmware version 7.10 and later.

Always use the latest camera drivers (ASCOM or Camera SDK DLLs in Windows, INDI or libraries in Linux) available on the web. Also, always update the firmware in the Moravian Camera Ethernet Adapter if the camera is connected over Ethernet.

Cooling and power supply

Regulated thermoelectric cooling is capable to cool down the CMOS sensor to 45 °C below ambient temperature. The Peltier hot side is cooled by fans. The sensor temperature is regulated with ±0.1 °C precision. High temperature drop and precision regulation ensure very low dark current for long exposures and allow proper image calibration.

The airflow is slightly different between C5A and C5S models.

- C5A camera air intake is located on the top side of the camera head; hot air output vents are on the camera back side.
- C5S camera air intake is on the camera bottom and output vents are on top.

Figure 10: The C5S (left) and C5A (right) camera vents

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.

Sensor cooling	Thermoelectric (Peltier modules)
Cooling ΔT	45 °C below ambient regulated
	48 °C below ambient maximum
Regulation precision	±0.1 °C
Hot side cooling	Forced air cooling

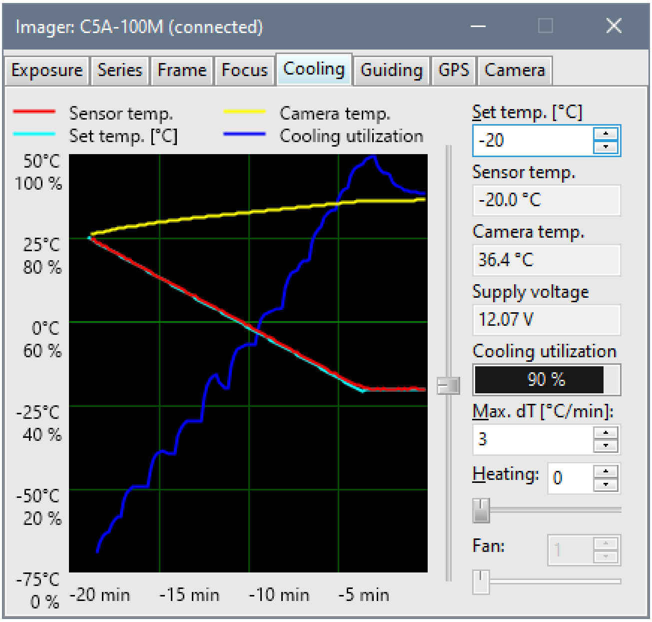


Figure 11: C5A-100M camera reaching regulated -45°C sensor temperature below ambient temperature

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 C5 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, 120 W “brick” adapter is supplied with the camera. Although the camera power consumption does not exceed 60 W, the 120 W power supply ensures noise-free operation.

The power connector on the C5 camera head differs from the 5.5/2.5 mm power plug, used on other Cx camera lines, because of the higher power draw of the C5 cameras. New power connector also ensures safer connection.

Camera head supply	12 V DC
Camera head power consumption	<9 W without cooling
	60 W maximum cooling
Power connector	4-pin plug
Adapter input voltage	100-240 V AC/50-60 Hz

Adapter output voltage	12 V DC/10 A
Adapter maximum power	120 W

Stated 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 voltage drops below 12 V.

C5 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 12:Figure 8: 12 V DC/10 A power supply adapter for the C5 camera

Mechanical Specifications

Compact and robust camera head measures only 154×154×76 mm (approx. 6×6×3 inches).

The head is CNC-machined from high-quality aluminum and black anodized. The head itself contains USB-B (device) connector and 4-pin 12 V DC power plug, no other parts, except a “brick” power supply, are necessary. Another connector on the camera head allows control of optional external filter wheel.

Integrated mechanical shutter of the C5A models allows automatic dark frame exposures, which are necessary for unattended, robotic setups.

Internal mechanical shutter	C5A yes, blade shutter
	C5S no
Camera head dimensions	154 × 154 × 76 mm
Camera head weight	1.9 kg (without filter wheel)
	2.8 kg (with the external filter wheel)

C5A camera head front view

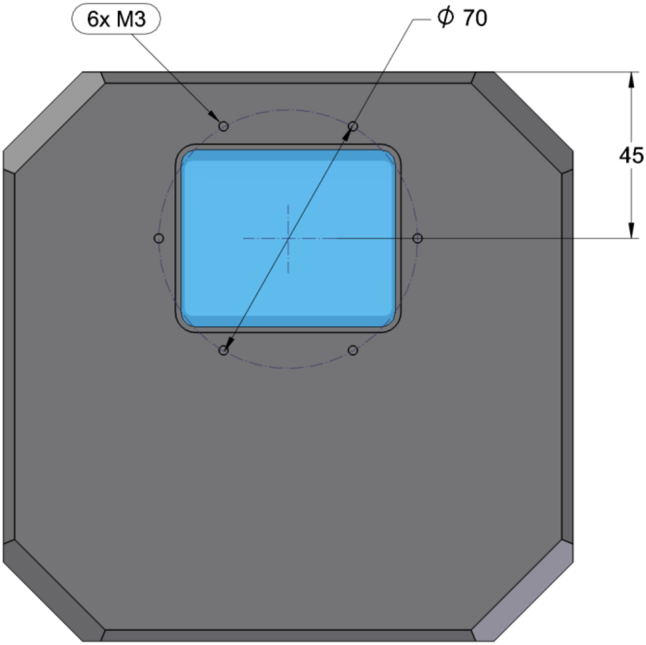


Figure 13: C5A camera head interface for filter wheel or tiltable adapter base

Filter wheels or tiltable adapter base are attached to the camera head using six M3 screws around the 70 mm diameter ring.

C5A camera with M85×1 threaded adapter

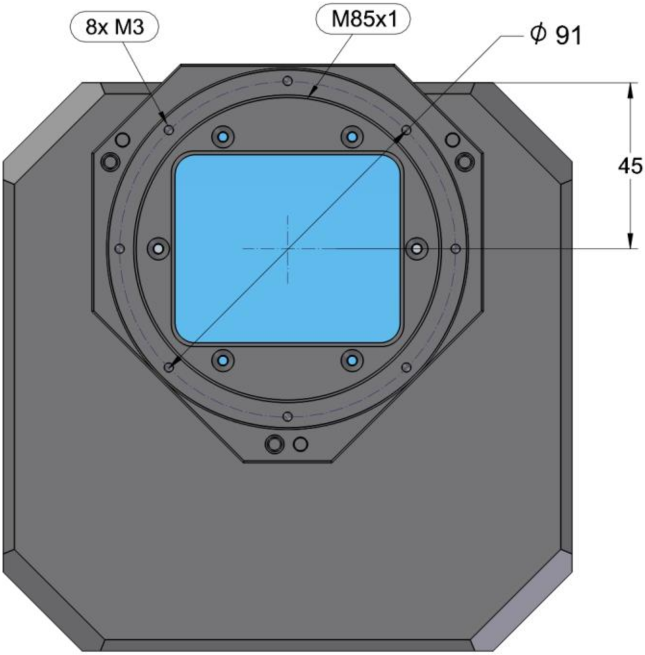


Figure 14: C5A camera head with M85×1 adapter

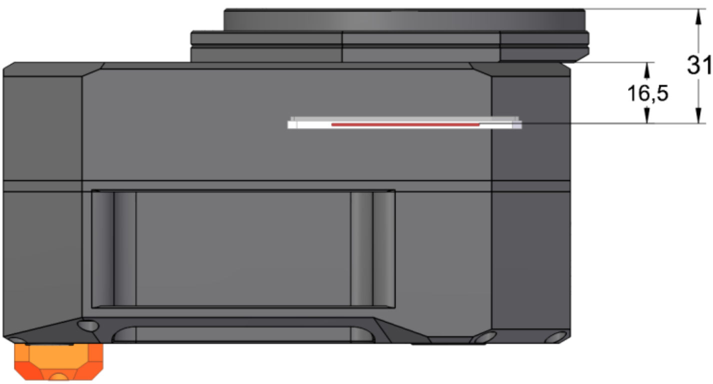


Figure 15: C5A camera head with M85×1 adapter Back Focal Distance

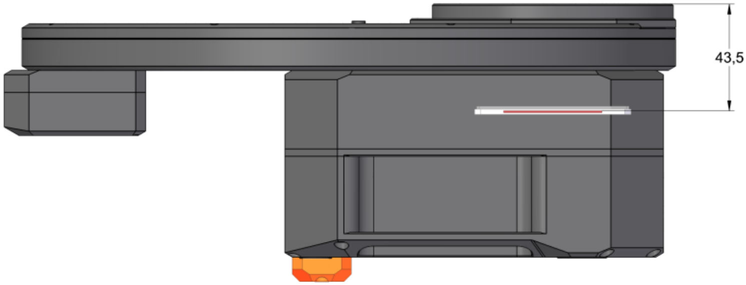


Figure 16: C5A camera with External Filter wheel with M85×1 adapter Back Focal Distance

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.

Note the M85×1 adapter is also equipped with eight M3 threaded holes arranged around the 91 mm diameter circle. These threaded holes provide alternative mean of camera attachment to the optical system.

C5A camera with M68×1 threaded adapter

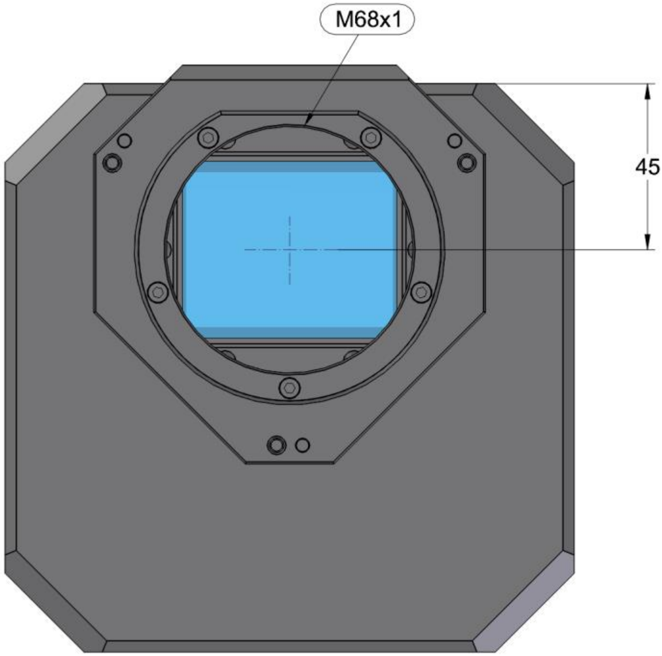


Figure 17: C5A camera head with M68×1 adapter

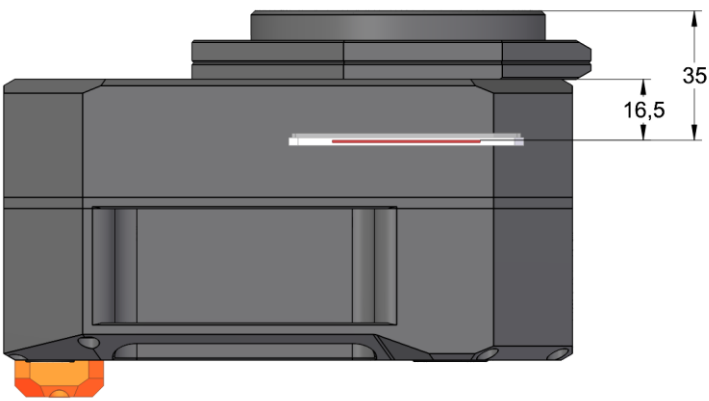


Figure 18: C5A camera head with M68×1 adapter Back Focal Distance

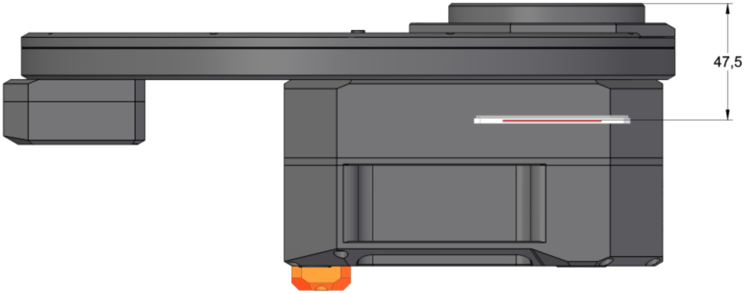


Figure 19: C5A camera with External Filter wheel with M68×1 adapter Back Focal Distance

C5A camera with C5-OAG with M85×1 thread

C5-OAG is designed to be used with the XL-sized External filter wheels only.

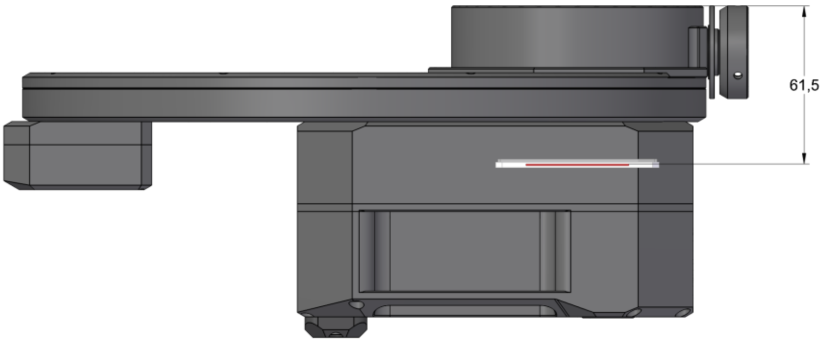


Figure 20: C5A camera with External Filter wheel with C5-OAG Back Focal Distance

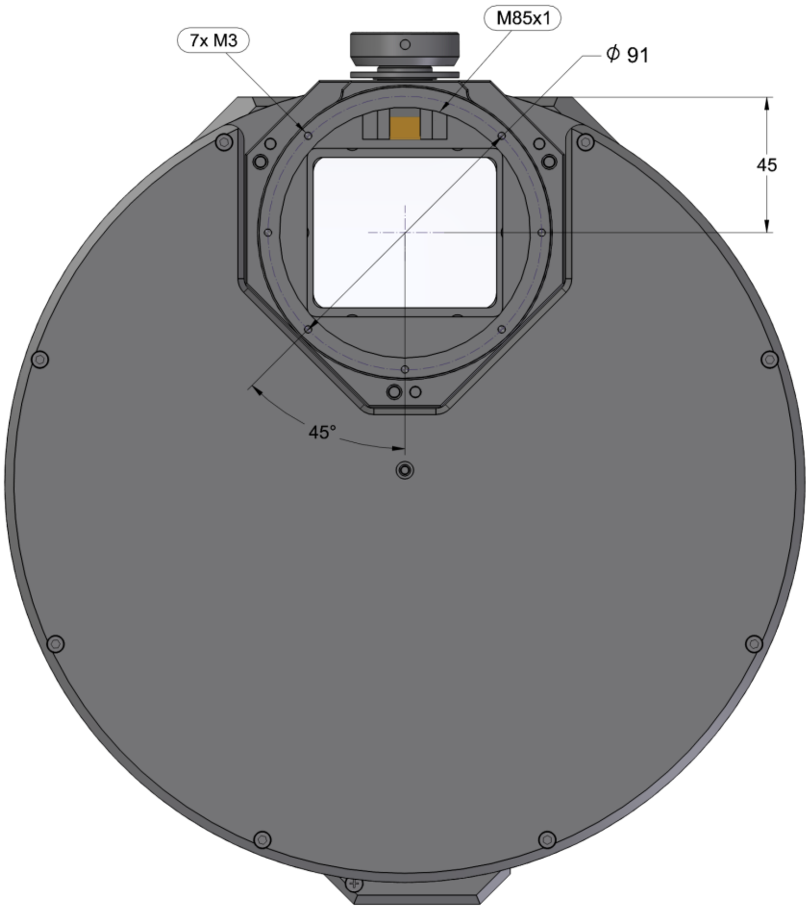


Figure 21: C5A camera with External Filter wheel with C5-OAG

C5S camera head front view

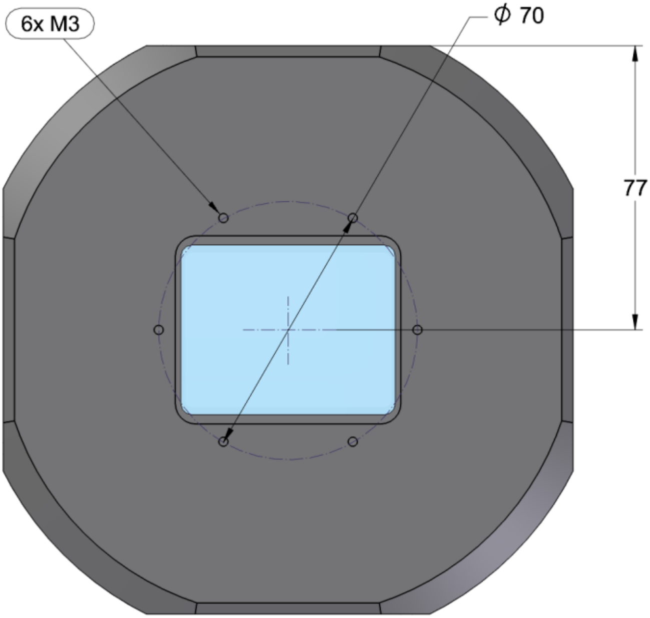


Figure 22: C5S camera head interface for filter wheel or tiltable adapter base

Filter wheels or tiltable adapter base are attached to the camera head using six M3 screws around the 70 mm diameter ring.

C5S camera with M85×1 threaded adapter

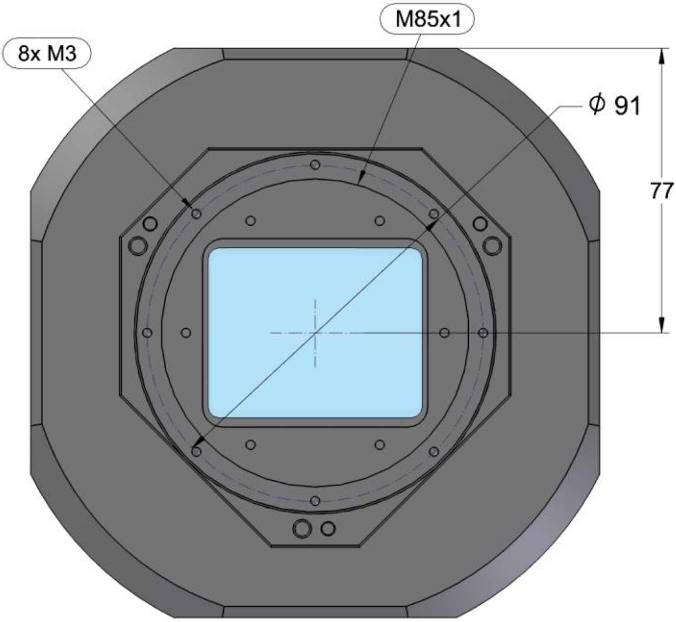


Figure 23: C5S camera head with M85×1 adapter

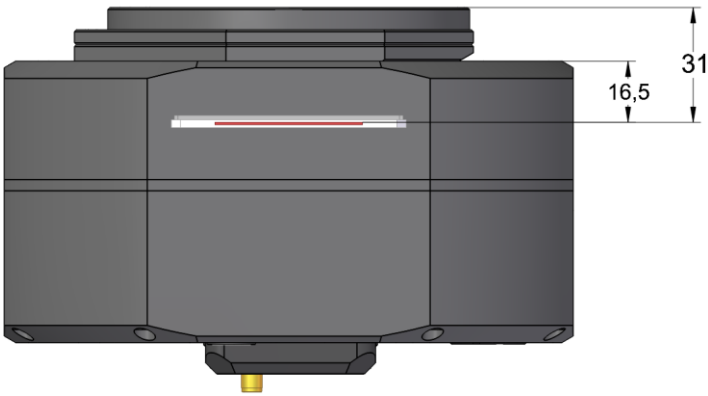


Figure 24: C5S camera head with M85×1 adapter Back Focal Distance

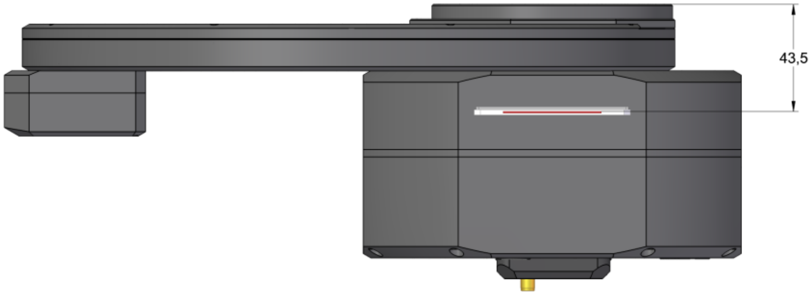


Figure 25: C5S camera with External Filter wheel with M85×1 adapter Back Focal Distance

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.

Note the M85×1 adapter is also equipped with eight M3 threaded holes arranged around the 91 mm diameter circle. These threaded holes provide alternative mean of camera attachment to the optical system.

C5S camera with M68×1 threaded adapter

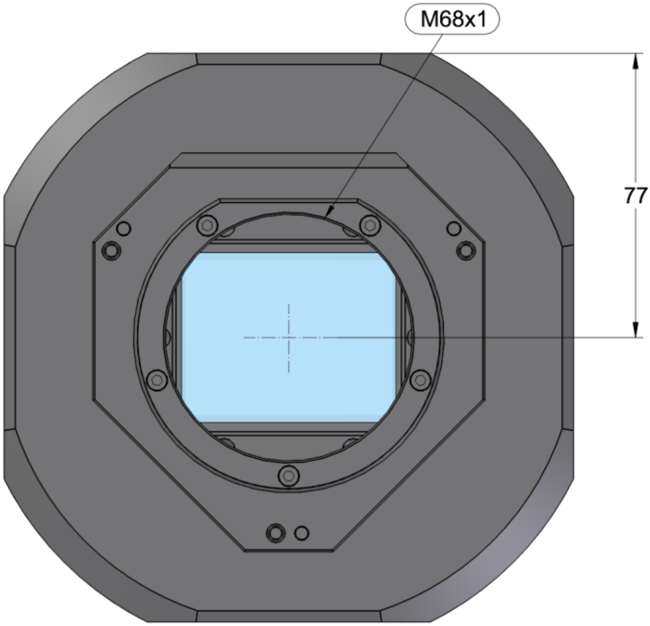


Figure 26: C5S camera head with M68×1 adapter

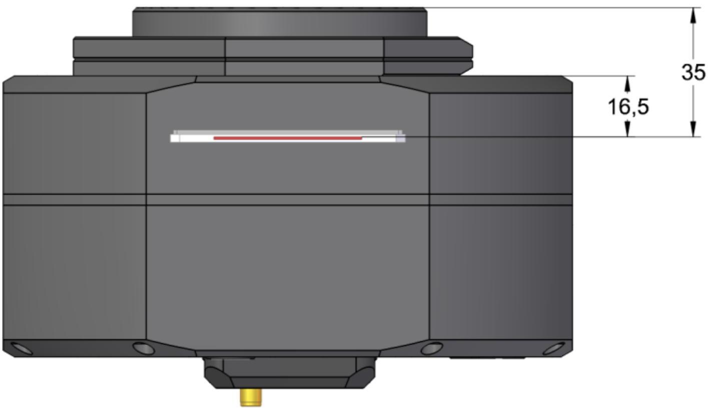


Figure 27: C5S camera head with M68×1 adapter Back Focal Distance

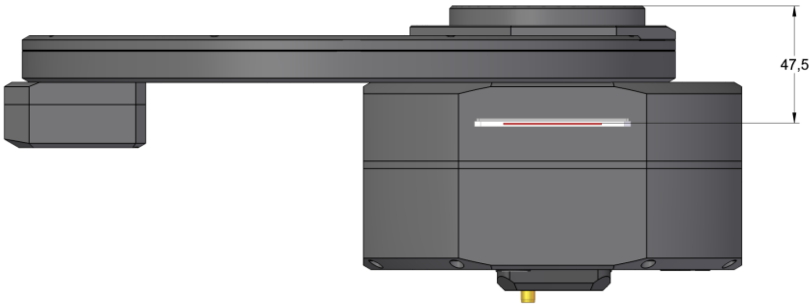


Figure 28: C5S camera with External Filter wheel with M68×1 adapter Back Focal Distance

C5S camera with C5-OAG with M85×1 thread

C5-OAG is designed to be used with the XL-sized External filter wheels only.

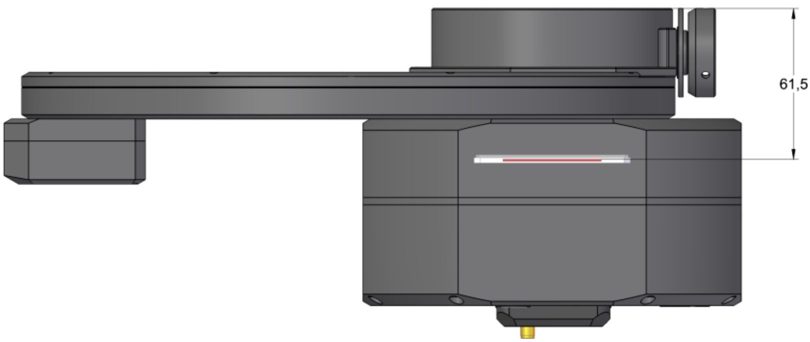


Figure 29: C5S camera with External Filter wheel with C5-OAG Back Focal Distance

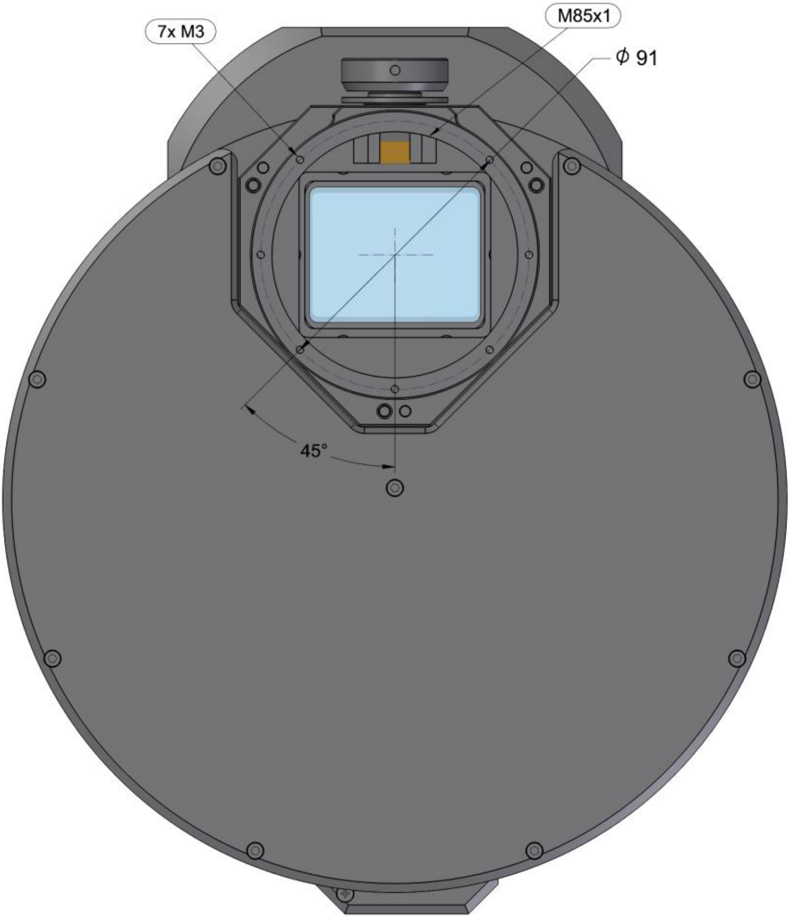


Figure 30: C5S camera with External Filter wheel with C5-OAG

Filter distance to sensor

It is necessary to know the distance of the filter entrance aperture from the sensor to calculate possible vignetting (partial shielding of the sensor edge parts from the incoming lights). In the case of C5 cameras, this is technically not an "aperture", as the filters are squares. So, instead of comparing filter aperture diameter to sensor diagonal, filter hole linear dimension must be compared longer side of the sensor.

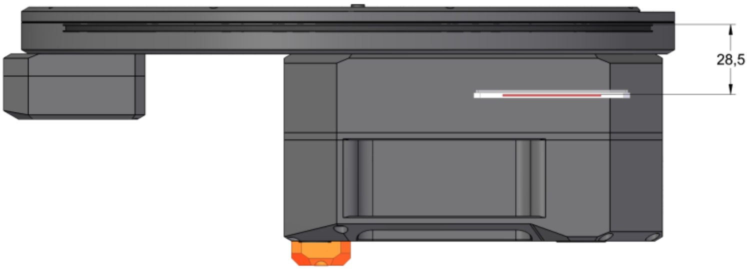


Figure 31: Distance of the filter wheel entrance pupil from the sensor

The 7-positions filter wheel for 50×50 mm filters entrance dimension is 48 mm, 5-positions filter wheel for 65×65 mm filters entrance dimension is 63 mm. The C5A-100M sensor longer side measures 43.86 mm, while the C5A-150M sensor longer side measures 53.42 mm.

Optional accessories

Various accessories are offered with C5 cameras to enhance functionality and help camera integration into imaging setups.

External filter wheels

The C5 camera contains electronics and an 8-pin connector on the camera head to control filter wheels. As the mechanical interface of the C5 cameras, intended to attach filter wheels, differs from the interface on the C3 or C4 cameras (see the chapter **Camera head front view** of the **Mechanical Specification** section for details), C5 cameras are not compatible with the "M" or "L" external filter wheels intended for C3 or C4 lines. New "XL" size external filter wheel is designed especially for the C5 series.

Figure 32: C5 camera with the "XL" filter wheel attached

The "XL" filter wheel housing can accommodate two filter wheels:

- 5-positions filter wheel for 65×65 mm filters
- 7-positions filter wheel for 50×50 mm filters

Note the 50×50 mm filters are suitable for C5A-100M cameras only, as the filter would partially shade sides of the large sensors of the C5A-150M camera.

Telescope adapters

There are basically only two types of telescope adapters, available for C5 cameras:

- M85×1 threaded adapter, intended for both C5A-100M and C5A-150M camera models. This adapter is also equipped with eight M3 threaded holes arranged around the 91 mm diameter circle, providing alternative possibility to attach the C5 camera to the optical system.
- M68×1 threaded adapter, suitable for C5A-100M camera only due to limited aperture, possibly causing vignetting of the large sensor of C5A-150M camera.

Both adapters have adjustable tilt and both can be mounted either on the adapter base on the camera head or on the External filter wheel front plane.

> Note the Back Focal Distances of these adapter are slightly different because of differences in mechanical design. BFD also varies for adapter mounted directly on the camera head or on the filter wheel. Refer to the **Mechanical Specification** chapter for exact BFD values, please.

Off-Axis Guider Adapter (OAG)

C5 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.

C5-OAG is manufactured with M85×1 thread with the back focal distance 61.5 mm.

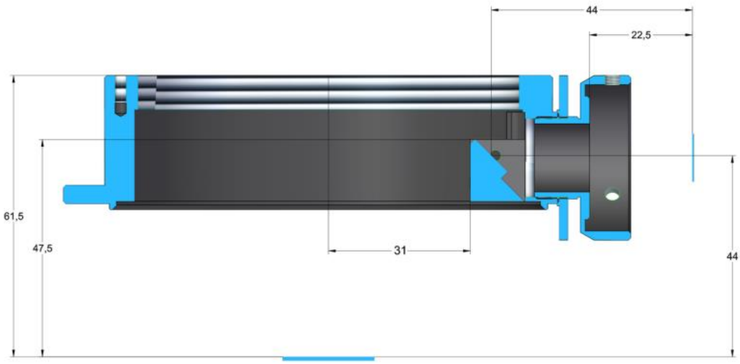


Figure 33: Position of the OAG reflection mirror relative to optical axis

The C5-OAG is designed for cameras using the XL-size external filter wheel. The guiding camera will not be able to reach focus is the OAG is mounted directly to the camera head.

OAG guider port is compatible with C0 and C1 cameras when mounted on the C5A camera. Mechanical constrains of the C5S camera head allows usage of only smaller C0 models. 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 C5-OAG.

Figure 34: OAG on C5 camera with External filter wheel

GPS receiver module

The C5 cameras can be equipped with an optional GPS receiver module, which allows very precise timing of the exposure times. Geographic location data are also available to the control software through specific commands.

The used GPS receiver is compatible with GPS, GLONASS, Galileo and BeiDou satellites.

The GPS receiver can be attached to the back side of the camera head, between the power and USB connectors. If the camera is not equipped with the GPS module, the GPS port is covered with a flat black cover.

Figure 35: The C5A camera with GPS receiver module with external antenna

Figure 36: The C5S camera with GPS receiver module with external antenna

Please note if the GPS module is to be added later, the camera must be sent to manufacturer. Just connecting the GPS module to available port is not enough, it is also necessary to reconfigure the camera firmware.

GPS receiver module handling

GPS antenna is shipped with the GPS module. Antenna cable is 3 m long and the antenna is equipped with a magnet, allowing it to be attached to any ferromagnetic surface. Please note the antenna must have a good view to the sky to be able to acquire signal from GPS satellites. Placing the antenna e.g. under metal covered dome may significantly limit the GPS signal reception.

GPS module is handled through camera command set. Its main purpose is to provide very precise timing of the exposure times with μs precision (the GPS module provides time pulses with 30 ns tolerance). Geographic location data are also available to the control software through specific commands.

Spare desiccant containers

The C5 cameras are supplied with silicagel container, intended to dry the sensor cold chamber. This container can be unscrewed and desiccant inside can be dried in the oven.

Container shipped with the camera by default does not exceed the camera head outline. It is equipped with a slot for tool (or for just a coin), allowing releasing and also tightening of the container.

It is possible to order spare container, which makes desiccant replacement easier and faster. It is possible to dry the spare container with silicagel and then only to replace it on the camera. Spare container is supplied including the air-tight cap.

Spare container can be supplied also in a variant that allows manipulation without tools. But this container is longer and exceeds camera outline. If the space behind the camera is not critical, this container can make desiccant exchange even easier.

Figure 37: Optional cap, standard and tool-less container variants

Moravian Camera Ethernet Adapter

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

Figure 38: The Moravian Camera Ethernet Adapter with two connected cameras

Adjusting of the telescope adapter

All telescope/lens adapters of the C5 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 39: 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 C5 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 40: 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.

Camera Maintenance

The C5 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 C5 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 C5 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 41: Silica-gel container is accessible from the camera back side

Exchanging the silica-gel

C5 cameras employ the same desiccant container like the C3 and C4 Enhanced Cooling 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 42: 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.

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 C5 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 43: 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, 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, shipped with the camera, return the camera to the service center for repair.