C1+ Series

Astronomical Cameras

User's Guide

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Table of Contents

Introduction

Thank you for choosing the Moravian Instruments camera. C1+ camera models are designed to fulfil the gap between small and lightweight C1 models, intended as Moon and planetary cameras and auto-guiders, and C2 cameras, equipped with active sensor cooling and mechanical shutter and thus intended for more serious astronomical imaging and research. C1+ cameras can work as C1 ones, only being somewhat heavier and bulkier, and at the same time C1+ can replace the cooled C2 models, only with slightly less cooling performance and lack of mechanical shutter.

C1+ cameras with **global shutter** CMOS sensors are designed to be able to operate from USB power lines only. However, some functions are available only if external 12 V DC power supply is connected. C1+ functions equal to C1 cameras when **powered from USB** only:

- Image acquisition.
- Mount guiding through standard "autoguider" 6-pin connector.

When a **12 V DC power** is plugged in, C1 camera functions extend with:

- Active and regulated sensor cooling with Peltier cooler.
- Ability to control external filter wheel.

The C1+ cameras with **rolling shutter** CMOS sensors always require the 12 V DC power.

Still, C1+ capabilities lack some functionality, available in larger and heavier C2 cameras only:

- C1+ have no mechanical shutter, necessary for automatic dark and bias frame acquisition in remote or robotic setups.
- C1+ lack the possibility to use internal filter wheel.
- C1+ cooling performance is slightly lower than in the case of C2, but the sensor temperature difference is only a few degrees Celsius.

Mechanical design of this series makes it fully compatible with vast range of telescope adapters, off-axis guider adapters, internal or external filter wheels, Camera Ethernet adapters, guiding cameras etc.

Rich software and driver support allows usage of C1+ 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, shipped with the camera, provide the way to integrate C1+ camera with broad variety of camera control programs.

The C1+ 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 slow-scan, 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 compatible with a PC standard 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.

C1+ cameras are designed to be attached to host PC through very fast USB 3.0 port. While C1+ 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 Gx) cameras of any type (not only C1+, but also C1, C2, C3 and 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 while the USB standard allows usage of cable no longer than approx. 5 meters, 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.

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.

Figure 1: Comparison of the C1+ camera head (middle) with C1 camera (left) and C2 camera (right)

C1+ Camera Overview

C1+ camera head is designed to be as small and compact as a cooled camera with rich features and compatible with broad set of accessories can be.

C1+ cameras are equipped with tiltable telescope interface and tripod mounting threaded holes. They are also compatible with external filter wheels designed for larger C2 cameras – camera head contains connector to control filter wheel. If the external filter wheel is used, the tiltable mechanism on the camera head is inactive and tiltable adapters for external filter wheels are used instead. Therefore, C1+ cameras can utilize vast range of telescope and lens adapters including off-axis guider adapters.

Figure 2: C1+ Camera without filter wheel (left) and with attached External filter wheel (right)

There are two sizes of the External filter wheels, each capable to accept two sizes of filters, available for the C1+ cameras:

- Extra small “XS” size wheel for 8 unmounted filters D31 mm or filters in 1.25” threaded cells.
- Extra small “XS” size wheel for 7 unmounted filters D36 mm.
- Small “S” size wheel for 12 unmounted filters D31 mm or filters in 1.25” threaded cells.
- Small “S” size wheel for 10 unmounted filters D36 mm.

C1+ cameras are manufactured with a wide range of CMOS sensors. Probably the most important differentiating factor, fundamentally affecting camera operation, is an electronic shutter implemented in the sensors. C1+ cameras support sensors with:

- **Global shutter**, allowing capturing of the whole frame in the very same instance of time. This means all pixels are reset and start to capture light simultaneously. Global shutter is particularly suitable for capturing fast moving scenes, because they ensure image does not suffer from motion distortion, caused by rolling shutter sensors. On the other side, frame rate of global shutter sensors is lower compared to rolling shutter ones, because each frame must be fully digitized prior to start of next exposure.
- **Rolling shutter**, which resets individual image rows in a sequence. The exposure of each image row is delayed typically by a few tens of microseconds. Depending on this delay and number of rows, the first and last row exposure time may be shifted by up to several tenths of a second. The inherent feature of rolling shutter sensors is a distortion of fast-moving scenes, when image moves within the time individual rows are exposed. Luckily, such fast moving scenes are very rare in astronomy. The plus side of rolling shutter is much higher FPS, as each image is already exposed while the previous image is digitized.

C1+ Camera System

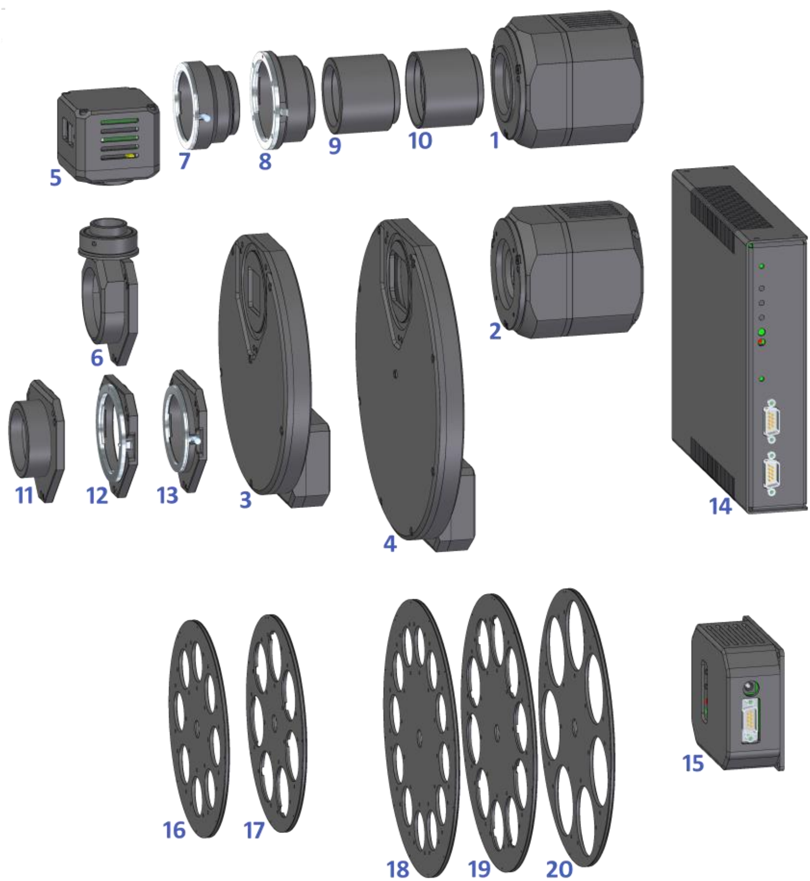


Figure 3: Schematic diagram of C1+ camera system components

Components of the C1+ Camera system include:

1. C1+ camera with C1 compatible adapter
2. C1+ camera with C2 compatible adapter

   When used without spring and pushing screws, this adapter also works as base for External filter wheels.

3. External Filter Wheel “XS” size (7 or 8 positions)
4. External Filter Wheel “S” size (10 or 12 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 OAG or on standalone guiding telescope.

6. Off-Axis Guider with M48×0.75 thread
7. C1 compatible Nikon bayonet adapter
8. C1 compatible Canon EOS bayonet adapter
9. C1 compatible M42×0.75 (T-thread) adapter, 55 mm BFD
10. C1 compatible M48×0.75 adapter, 55 mm BFD
11. C2 compatible M42×0.75 (T-thread) or M48×0.75 threaded adapter, 55 mm BFD
12. C2 compatible Canon EOS bayonet adapter
13. C2 compatible Nikon bayonet adapter
14. Camera Ethernet Adapter (x86 CPU)
15. 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 Cx cameras using routable TCP/IP protocol over unlimited distance.

16. 8-positions external filter wheel “XS” for 1.25”/D31 mm filters
17. 7-positions external filter wheel “XS” for D36 mm filters
18. 12-positions external filter wheel “S” for 1.25”/D31 mm filters
19. 10-positions external filter wheel “S” for D36 mm filters
20. 7-positions external filter wheel “S” for 2”/D50 mm filters

C1+ with global shutter CMOS Sensors

C1+ series of CMOS cameras with Sony IMX **global shutter** CMOS detectors have 3.45 × 3.45 µm or 4.50 × 4.50 µm square pixels.

All used sensors utilize global electronic shutter, which means every pixel within the image is exposed in the same time, as opposed to rolling shutter, which exposes individual lines one after another. There is no difference for long exposures of static objects, but imaging of moving objects using short exposure time using rolling shutter leads to image shape distortions.

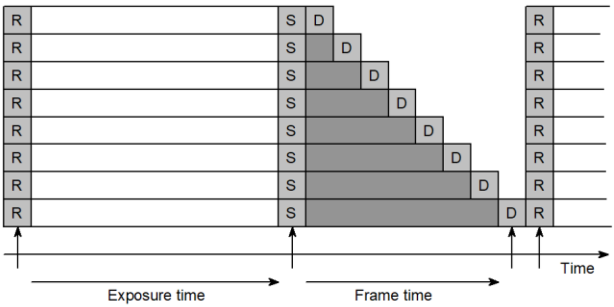


Figure 4: Illustration of the CMOS global shutter operation

Three lines of C1+ cameras are available depending on the available dynamic range (bit-depth of the digitized pixels) and pixel size:

- **C1+ cameras with Sony IMX sensors with 3.45 × 3.45 µm pixels, supporting 8- and 12-bit digitization.** Because every 12-bit pixel occupies two bytes when transferred to host PC, 12-bit image download time is longer compared to 8-bit image. Maximal FPS in 8-bit mode is then significantly higher.
- **C1+ cameras with Sony IMX sensors with 3.45 × 3.45 µm pixels, supporting 12-bit digitization only.** As the 12-bit read mode is always used for long-exposure applications (astronomical photography, scientific research) either way, lower theoretical download speed in 8-bit mode brings no limitations for real-world

scenarios. All other parameters being same (sensor size, resolution, pixels size, noise, …), lower price of "A" cameras may be then very attractive.

- **C1+ cameras with Sony IMX sensors with 4.50 × 4.50 µm pixels and 12-bit digitization only.** Greater pixels mean higher dynamic range (more electrons can be stored in each pixel before it saturates), but also higher read noise. Still the theoretical S/N is almost the same because of higher signal camera can accumulate. This camera is more suitable for longer focal length telescopes, where small pixels provide oversampled images, and also for research applications, where dynamic range is important.

C1+ camera models with 3.45 × 3.45 µm pixels and 8- and 12-bit digitization:

Model	**C1+3000**	**C1+5000**	**C1+12000**
CMOS sensor	IMX252	IMX250	IMX253
Resolution	2064 × 1544	2464 × 2056	4112 × 3008
Pixel size	3.45 × 3.45 µm	3.45 × 3.45 µm	3.45 × 3.45 µm
Sensor size	7.12 × 5.33 mm	8.50 × 7.09 mm	14.19 × 10.38 mm

C1+ camera models with 3.45 × 3.45 µm pixels and 12-bit digitization only:

Model	**C1+3000A**	**C1+5000A**	**C1+12000A**
CMOS sensor	IMX265	IMX246	IMX304
Resolution	2064 × 1544	2464 × 2056	4112 × 3008
Pixel size	3.45 × 3.45 µm	3.45 × 3.45 µm	3.45 × 3.45 µm
Sensor size	7.12 × 5.33 mm	8.50 × 7.09 mm	14.19 × 10.38 mm

C1+ camera models with 4.50 × 4.50 µm pixels and 12-bit digitization only:

Model	**C1+7000A**
CMOS sensor	IMX428
Resolution	3216 × 2208
Pixel size	4.50 × 4.50 µm
Sensor size	14.47 × 9.94 mm

Cameras limited to 12-bit read mode are marked with letter A, following the model number. For instance, if C1+3000 marks camera with both 8- and 12-bit read modes, C1+3000A denotes camera model with only 12-bit read mode. All other parameters (sensor size, pixel resolution) are equal.

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 C1+ cameras show very good linearity in response to light. This means the camera can be used also for entry-level research projects, like for instance photometry or brighter variable stars etc.

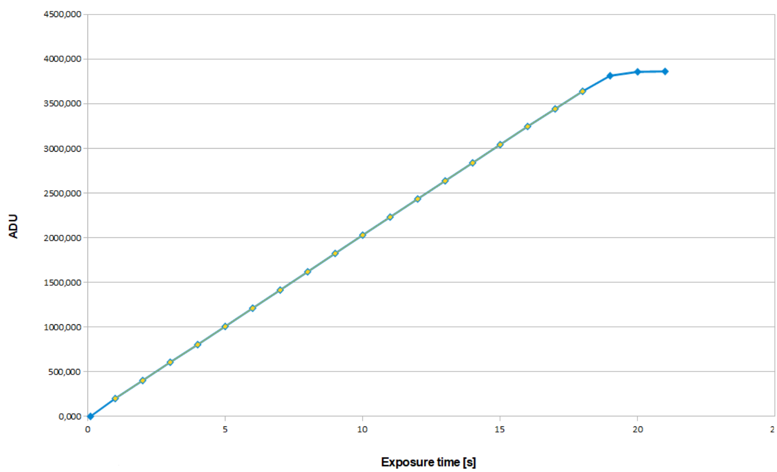


Figure 5: Response of the Sony IMX sensors with 3.45 × 3.45 µm pixels (IMX252)

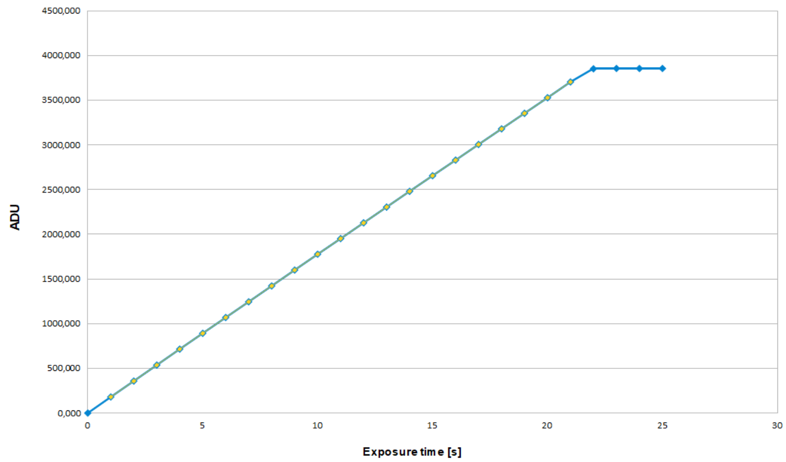


Figure 6: Response of the Sony IMX sensors with 4.50 × 4.50 µm pixels (IMX428)

Download speed

As already noted, there are two lines of C1+ camera series, differing in the used sensor. The first series with 3.45 × 3.45 µm pixels offers four different read modes:

- **8-bit slow** mode with ~132 MPx/s digitization speed
- **12-bit slow** mode with ~72 MPx/s digitization speed
- **8-bit fast** mode with ~263 MPx/s digitization speed
- **12-bit fast** mode with ~132 MPx/s digitization speed

The slow variant of both read modes can be used to slightly lower the amount of heat generated by the sensor, as the communication interface operates at half speed compared to fast mode. Also, when the camera is connected using USB 2.0 interface, fast read mode provides data at higher speed than the USB 2.0 can handle and thus causes more interruptions of image digitization process.

The "A" version of C1+ cameras with 3.45 × 3.45 µm pixels offers only single read mode:

- **12-bit fast** mode with ~132 MPx/s digitization speed

And the “A” version of C1+ cameras with 4.50 × 4.50 µm pixels offers also only one read mode:

- **12-bit fast** mode with ~151 MPx/s digitization speed

The digitization speeds mentioned above are valid for USB 3.0 connection. Also please note the digitization speeds do not necessarily lead to corresponding FPS, because every image downloaded has to be processed and displayed, which also consumes time. This time is negligible, if slow-scan camera needs many seconds for image download, but in the case of fast CMOS cameras, time for image processing in the PC (e.g. calculation of image standard deviation etc.) can be longer than image download itself.

Despite one byte per pixels is transferred from camera to PC in the 8-bit read mode, many astronomical processing software packages work with 16-bit or 32-bit images only (e.g. SIPS). So, images occupy the same space in the computer memory regardless of the read mode.

Also, standard format for image storage in astronomy is FITS. While this format supports 8-bit per pixel, this variant is rather unusual and 16 or 32-bit integer or 32-bit floating-point pixels are typically stored to disk files to achieve as wide compatibility as possible.

Camera gain

Sensors used in C1+ cameras offer programmable gain from 0 to 24 dB, which translates to the output signal multiplication from 1× to 15.9×. Gain can be set with 0.1 dB step.

Note the C1+ 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.

Conversion factors and read noise

Generally, all sensor characteristics depend on the used gain. So, we provide two list of parameters for both minimal and maximal gain.

Camera/sensor parameters for sensors with 3.45 × 3.45 µm pixels:

Digitization	12-bit	12-bit	8-bit	8-bit
Sensor gain	0 dB	24 dB	0 dB	24 dB
Full well capacity	11000 e-	1100 -e	2600 e-	1100 e-
Conversion factor	2.8 e-/ADU	0.3 e-/ADU	10.0 e-/ADU	4.4 e-/ADU
Read noise	2.2 e- RMS	2.0 e- RMS	4.2 e- RMS	9.7 e- RMS

Camera/sensor parameters for sensors with 4.50 × 4.50 µm pixels:

Digitization	12-bit	12-bit
Sensor gain	0 dB	24 dB
Full well capacity	26000 e-	2100 -e
Conversion factor	6.3 e-/ADU	0.5 e-/ADU
Read noise	5.3 e- RMS	3.9 e- RMS

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.

Exposure control

C1+ cameras are capable of very short exposures. The shortest exposure time is 125 µs (1/8000 of second). This is also the step, by which the exposure time is expressed. So, the second shortest exposure is 250 µs etc.

Long exposure timing is controlled by the host PC and there is no upper limit on exposure time. In reality the longest exposures are limited by saturation of the sensor either by incoming light or by dark current (see the following sub-chapter).

Internal mechanical shutter	No
Shortest exposure time	0.000125 s (electronic shutter)
Longest exposure time	Limited by chip saturation only

C1+ with rolling shutter CMOS Sensors

C1+ series of CMOS cameras with Sony IMX **rolling shutter** CMOS detectors employs sensors of two different sensor families, differing in pixel size and dynamic range:

Model	**C1+9000**	**C1+46000**
CMOS sensor	IMX533	IMX492
Resolution	3008 × 3008	8336 × 5648
Pixel size	3.76 × 3.76 µm	2.315 × 2.315 µm
Digitization	14-bit	12-bit
Sensor size	11.31 × 11.31 mm	19.30 × 13.08 mm

The IMX533 sensor (C1+9000) belongs to the same family like sensors used in the C1×, C3 and C5 camera lines, only the digitization precision is 14-bit instead of 16-bit of the larger sensors.

The IMX492 sensor (C1+46000) offers the smallest pixels of all Moravian camera lines and it is unique for the C1+ and C2 camera lines.

As opposed to global-shutter sensors, rolling-shutter sensors expose individual lines in sequence.

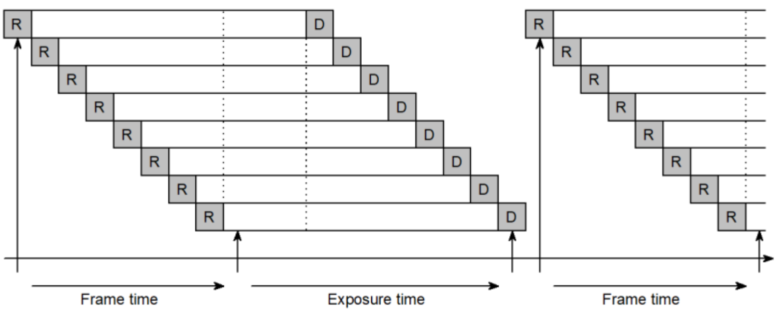


Figure 7: Illustration of the CMOS rolling shutter operation for individual exposures

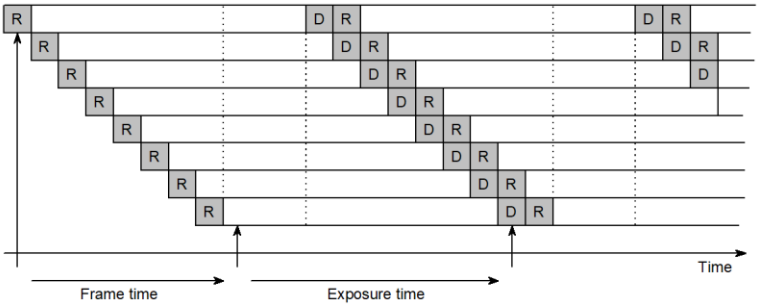


Figure 8: Illustration of the CMOS rolling shutter operation for serial exposures

The sensor belongs to the same family like sensors used in the C1×, C3 and C5 camera lines, only the digitization precision is 14-bit instead of 16-bit of the larger sensors.

Camera Electronics

Controlling of the rolling shutter sensors differs significantly from controlling of the global shutter sensors. The camera internals differ significantly according to different electronic shutter

The C1+ cameras with rolling shutter contain 256 MB of onboard memory, capable to store up to 14 full-resolution frames of the C1+9000 camera or 2 full-resolution frames in the case of C1+46000 camera. Camera API allows for sequential exposures, during which short-exposure images are stored into memory possibly faster than the host computer is able to read them. Sequential exposures are paused when the internal memory is filled with images, not yet read by the host PC. As explained earlier, rolling shutter sensors are capable to perform image exposure while digitizing the previous image.

Sensor linearity

The IMX sensors used in the C1+ camera shows 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.

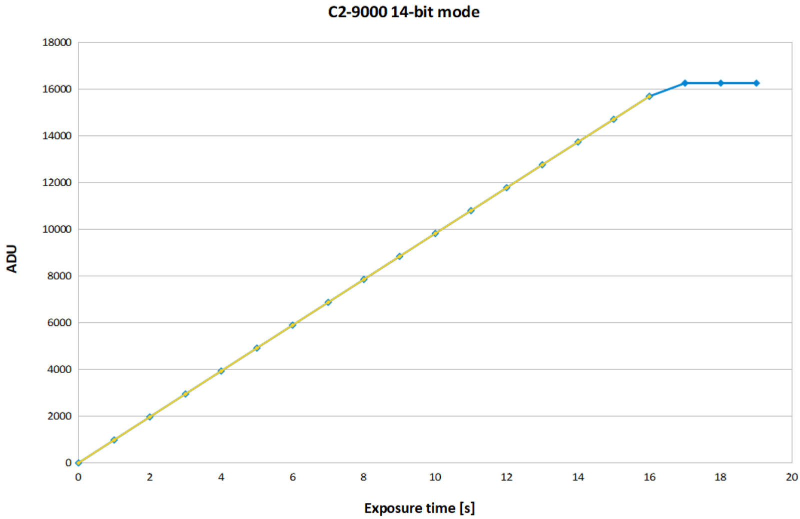


Figure 9: Response of the Sony IMX rolling-shutter sensor (IMX533)

Download speed

Thanks to C1+ camera onboard RAM, downloading of the image to the host computer 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	C1+9000	C1+46000
Full-frame, USB 3.0 (5 Gbps)	0.06 s	0.30 s
Full-frame, USB 2.0 (480 Mbps)	0.40 s	2.06 s

The C1+9000 camera significantly speeds up the download if only a sub-frame is read. However, the download time is not cut proportionally to number of pixels thanks to some fixed overhead time, independent on the sub-frame dimensions.

The download speedup is not as proportional to the downloaded area in the case of C1+46000 camera because of the sensor-imposed limitations, but it is still significant.

Camera model	C1+9000	C1+46000
1024×1024 sub-frame, USB 3.0 (5 Gbps)	0.02 s	0.08 s
1024×1024 sub-frame, USB 2.0 (480 Mbps)	0.05 s	0.14 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.

The C1+ 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	C1+9000	C1+46000
Full-frame 2×2 binning, USB 3.0 (5 Gbps)	0.03 s	0.19 s
Full-frame 2×2 binning, USB 2.0 (480 Mbps)	0.11 s	0.52 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 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 C1+9000 full frame is less than 0.5 s.

C1+9000 camera gain

Sensors used in C1+9000 camera offer programmable gain from 0 to 36 dB, which translates to the output signal multiplication from 1× to 63×.

> Note the C1+ 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×

C1+46000 camera gain

The C1+46000 camera offers programmable gain from 0 to 16 dB, which translates to the output signal multiplication from 1× to 6.5×.

> Note the C 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 500. 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×
100	1.61	1.20×
200	3.59	1.51×
300	6.15	2.03×
400	9.81	3.09×
500	16.25	6.49×

C1+9000 conversion factors and read noise

Generally, many sensor characteristics depend on the used gain. Also, the sensor used in C1+9000 employs two conversion paths[1]. 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 e- RMS to ~1.5 e- RMS.

Gain number	0	2749	2750	4030[2]
Sensor gain	0.0 dB	9.7 dB	9.7 dB	36 dB
	1×	3×	3×	63×
Full well capacity	50800 e-	16500 e-	16500 e-	11400 e-
Conversion factor	3.10 e-/ADU	1.02 e-/ADU	1.02 e-/ADU	0.69 e-/ADU
Read noise	3.81 e- RMS	3.03 e- RMS	1.55 e- RMS	1.46 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:

[1] The C1+9000 firmware must be updated to version at least 10.x to be able to utilize the High Gain Conversion.
[2] The 36 dB (63×) gain at register value 4030 is properly implemented only in C2-9000 firmware version 12.x and later.

- At gain = 0, dynamic range is 50800 / 3.81 = 13333×
- At gain = 2750, dynamic range is 16500 / 1.55 = 10645×

Also, it is worth noting that in reality the noise floor is not always 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 if 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 dominant source of noise is the sky glow.
  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 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.

C1+46000 conversion factors and read noise

The sensor read noise and full well capacity depend on the used gain.

Gain number	0	500
Sensor gain	0.0 dB	16.25 dB
	1×	6.49×
Full well capacity	18500 e-	2900 e-
Conversion factor	4.53 e-/ADU	0.71 e-/ADU
Read noise	7.11 e- RMS	5.29 e- RMS

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 C1+9000 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. Binnig with CMOS sensors can behave differently, pixels can be either added or averaged.

In theory, the resulting S/N ratio of binned pixel remains the same regardless if we add or average them. Let us 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 $\sqrt{(\sqrt{2})^2 + (\sqrt{2})^2}$. 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 $\frac{\sqrt{(\sqrt{2})^2+(\sqrt{2})^2}}{4}$. Resulting S/N also increases 2-times, but only until the noise decreases to lowest possible 1-bit of dynamic range.

But resulting S/N ratio can be affected either by overflow (saturation) of resulting pixel when adding binned pixels or by read noise underflow (dropping below 1 bit) when averaging them.

While the bigger siblings of the C1+9000 camera (C1×, C3, and C5) utilize CMOS sensors with full 16-bit dynamic resolution, the sensor used in C1+9000 offers only 14-bit conversion. So, up to 4 pixels (2×2 binning) can be added and still the resulting pixel cannot overflow the 16-bit dynamic range of each 2 bytes long pixel. This is why the default binning behavior of the C1+9000 camera uses pixel adding instead of averaging on both software binning and in-camera (hardware) binning.

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

```
[driver]
BinningSum = false
```

Let us 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 never 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 C1+9000 camera is 49 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 is also 100 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 37 ms.

There is no theoretical limit on maximal exposure length, but 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).

Cooling and power supply

As mentioned in the introduction, C1+ cameras with global shutter CMOS sensors can operate only with USB power (variants with rolling shutter sensors need 12 V DC all the time). Camera is then capable to acquire images and to control (guide) telescope mount via “autoguider” port. However, active sensor cooling, as well as filter wheel operation, is available only if external 12 V DC power supply is connected.

Camera fan operates even without 12 V DC power attached, only with lower fan speed. This helps to keep the camera electronics temperature close to environment temperature. When the 12 V DC power is plugged in, the fan turns to full speed to remove the heat generated by the Peltier thermo-electric cooler.

Regulated thermoelectric cooling is capable to cool the CMOS sensor more than 40 °C below ambient temperature. The Peltier hot side is cooled by fan. 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.

Figure 10: C1+ air inlet with fan is on the bottom side of the camera head (left), air outlet vents are on the camera top side (right)

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.

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	~45 °C below ambient
Regulated cooling ΔT	40 °C below ambient (~90% cooling)
Regulation precision	±0.1 °C
Hot side cooling	Forced air cooling (fan)

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.

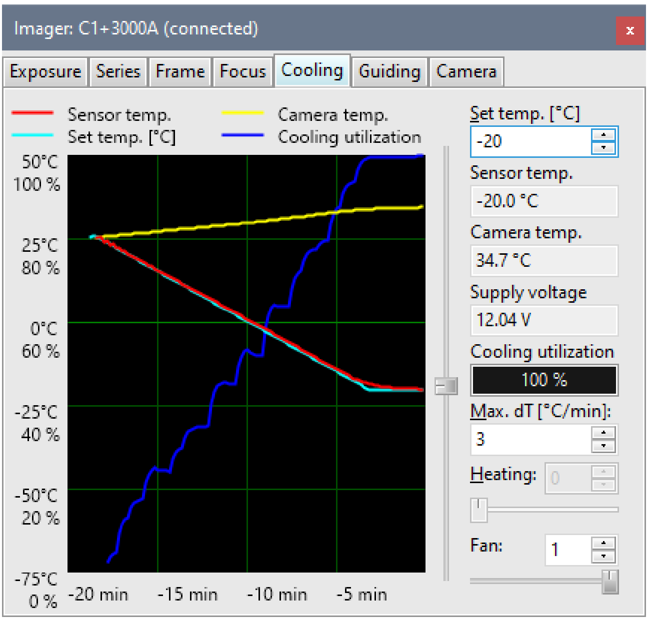


Figure 11: C1+3000A camera reaching maximum -45°C sensor temperature below ambient

Power supply

Certain camera functions need 12 V DC power supply. Power can be sourced from 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 25 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	<1 W without cooling
	22 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 can be powered by unregulated 12 V DC power source – the input voltage can be anywhere between 10 and 14 V. However, cooling efficiency can degrade if the supply drops below 12 V.

C1+ 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 the camera is powered from batteries.

Figure 12: 12 V DC/5 A power supply adapter for C1+ camera

Autoguider port

A lot of astronomical telescope mounts (especially the mass-manufactured ones) are not precise enough to keep the star images perfectly round during long exposures without corrections. Cooled astronomical cameras and digital SLR cameras allow perfectly sharp and high-resolution images, so even a small irregularity in mount tracking appears as star image deformations. Ability to automatically guide astronomical mounts built into C1+ cameras.

C1+ cameras are designed to operate without any mechanically moving parts (with the exception of magnetically levitating fan). Electronic shutter allows extremely short exposures and also obtaining thousands of images in a short time, which is necessary for quality guiding.

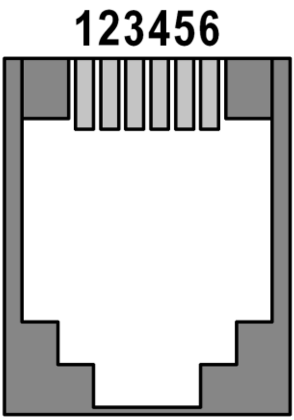
C1+ cameras work in connection with a host computer (PC). Guiding corrections are not calculated in the camera itself, it only sends acquired images to the PC. The software running on the PC calculates the difference from required state and sends appropriate corrections to the telescope mount. The plus side of using a host PC CPU to process images is the fact, that current PCs provide overwhelming computational power compared to any embedded processor inside the guiding camera. Guiding algorithms then can determine star position with sub-pixel precision, can match multiple stars to calculate average difference, which limits the effects of seeing, etc.

Calculated corrections can be sent back to mount using PC-to-mount link, but more accurate guiding can be achieved using so called “Autoguider” port. It is enough to connect the C1+ camera and the mount using standard 6-wire cable and guide the mount through the camera.

The maximum sinking current of each pin of the C1+ camera is 400 mA. If the mount does not treat the autoguider port as logical input only, but switches the guiding motors directly by these signals, a relay box must be inserted between the camera and the mount. The relay box ensures switching of currents required by the mount.

Figure 13: Standard 6-pin Autoguider Port is located close to the USB3 port on the back side of C1+ camera

The Autoguider port follows the de-facto standard introduced by SBIG ST-4 autoguider. The pins have the following functions:



1. R.A. + (Right)
2. Dec + (Up)
3. Dec – (Down)
4. R.A.– (Left)
5. Common (Ground)
6. Not connected

Mechanical Specifications

Compact and robust camera head measures only 78×78×80 mm (approx. 3.1×3.1×3.2 inches). The head is CNC-machined from high-quality aluminum and black anodized. The head itself contains USB-B (device) connector, Autoguider port connector, connector for External Filter Wheel and 12 V DC power plug.

The front side of the C1+ camera body is not intended for direct attachment of the telescope/lens adapter. It is instead designed to accept tiltable adapter base, on with the telescope and lens adapters are mounted. There are two variants of adapters available:

- **C1 compatible adapter base** with M42×0.75 (T-thread) and back focal distance (BFD) 18.5 mm.

  The 18.5 mm BFD equals to C1 camera with M42×0.75 adapter. Numerous extension adapters are available for C1 cameras, like M48×0.75 thread or M42×0.75 thread (T-adapter) with 55 mm BFD, Canon EOS and Nikon bayonets etc. All these adapters are then compatible with C1+ cameras.

  As opposed to C1 series, these adapters are mounted on the tiltable base and therefore can adjust optical axis if necessary.

- **C2 compatible adapter base** with 16.5mm BFD. This adapter is equipped with four M3 threaded holed 44 mm apart and also M48×0.75 thread.

  Note the 16.5 mm BFD equals to BFD of large cooled C2 cameras without filter wheel. Therefore, it is possible to attach all adapters for C2 cameras as well as external filter wheels to this adapter.

  When used with External filter wheel, this adapter base lacks the tilting spring and pushing screws, which are not necessary as the External filter wheel itself offer tiltable adapters intended for C2 cameras.

Of course, this adapter can be used without External filter wheel and then it provides M48×0.75 with very short 16.5 mm BFD.

Figure 14: C1+ camera with C1 compatible adapter (left) and with C2 compatible adapter (right)

Head dimensions	78×78×80 mm (without adapter base)
Back focal distance	18.5 mm (with C1 compatible adapter)
	16.5 mm (with C2 compatible adapter)
Camera head weight	0.68 kg

Back focal distance is measured from the sensor to the base on which adapters are mounted. Various adapters then provide back focal distance specific for the particular adapter type (e.g. M48 threaded adapter back focal distance is 55 mm).

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

C1+ Camera with C1 compatible adapter

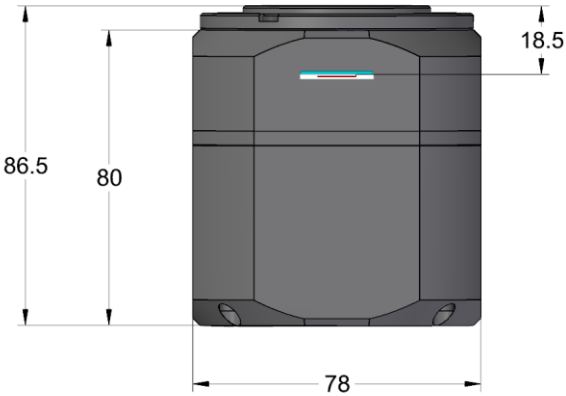


Figure 15: C1+ camera head with C1 compatible adapter side view dimensions

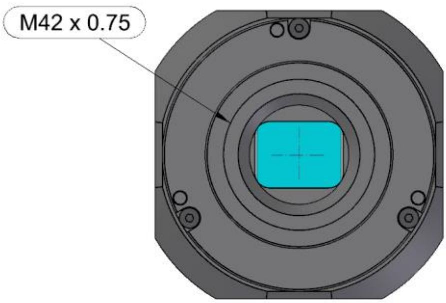


Figure 16: C1+ camera head with C1 compatible adapter front view dimensions

C1+ Camera with C2 compatible adapter

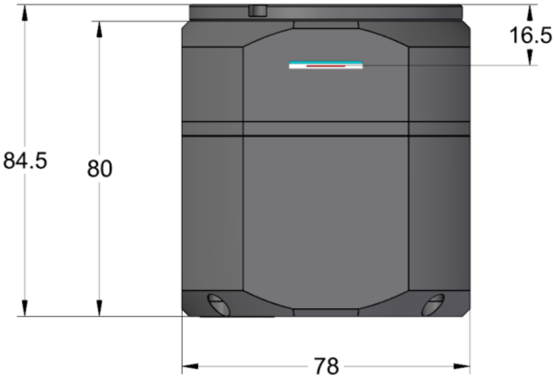


Figure 17: C1+ camera head with C2 compatible adapter side view dimensions

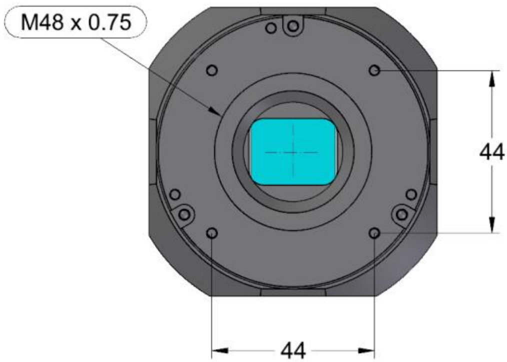


Figure 18: C1+ camera head with C2 compatible adapter front view dimensions

C1+ Camera with "XS" External Filter Wheel

C1+ cameras can be equipped with the same external filter wheels like the C2 cameras. In such case the C2 compatible adapter has to be used as a base for the External filter wheel.

Note the filter wheel can be used only if the C1+ camera is plugged to 12 V DC external power supply.

If the external filter wheel is used, tiltable adapters for C2 or G2 Mark II cameras must be used with it.

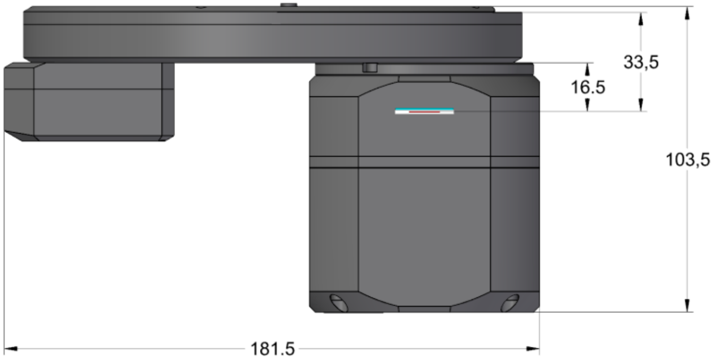


Figure 19: C1+ camera head with External filter wheel side view dimensions

Figure 20: C1+ camera head with External filter wheel bottom view dimensions

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

Optional accessories

Various accessories are offered with C1+ cameras to enhance functionality and help camera integration into imaging setups.

Telescope adapters

Telescope and lens adapters, intended for usage with C1+ cameras, are of two kinds:

- **Adapters for C1 cameras.** These adapters are mounted using M42×0.75 thread with 18.5 mm BFD. C1 compatible adapter base must be mounted on the C1+ camera head.
- **Adapters for C2 cameras.** C2 camera adapters are mounted on a tiltable base, which is manufactured on external filter wheel or on a standalone base if no filter wheel is used. Filter wheel or adapter base is mounted using four M3 threaded holes on a plate 16.5 mm from the sensor.
    - If a C2 adapter has to be used without filter wheel, a stack of two adapter bases must be used on C1+ camera – C2 compatible adapter base for C1+ camera and C2 adapter base on it. However, such combination is superfluous as majority of C2 adapter have an equivalent designed for C1 camera and thus can be used with C1 compatible adapter base.
    - The same tiltable adapter base is manufactured on the front plate of the external filter wheels. External filter wheel needs the C2 compatible adapter base attached to C1+ camera. Then all C2 adapters can be used.

Adapters for C1+ cameras with C1 compatible adapter base

Adapters are mounted to the C1 compatible adapter base, which provide titling mechanism.

- **T-thread with 55 mm BFD** – M42×0.75 inner thread adapter, preserves 55 mm back focal distance.
- **M48×0.75 with 55 mm BFD** – adapter with inner thread M48×0.75, preserves 55 mm back focal distance.

- **Nikon bayonet** – standard Nikon lens adapter, preserves 46.5 mm back focal distance.
- **Canon EOS bayonet** – standard Canon EOS lens adapter, preserves 44 mm back focal distance.

Figure 21: Adapters for C1 cameras, compatible with C1+ models

Adapters for C1+ cameras with C2 compatible adapter base and external filter wheel

C1+ uses the same External filter wheels like the C2 series. These External filter wheels are equipped with tiltable base, intended for adapters.

- **2-inch barrel** – adapter for standard 2" focusers.
- **T-thread short** – M42×0.75 inner thread adapter.
- **T-thread with 55 mm BFD** – M42×0.75 inner thread adapter, preserves 55 mm back focal distance.
- **M48×0.75 short** – adapter with inner thread M48×0.75.
- **M48×0.75 with 55 mm BFD** – adapter with inner thread M48×0.75, preserves 55 mm back focal distance.
- **Canon EOS bayonet** – standard Canon EOS lens adapter, preserves 44 mm back focal distance.
- **Nikon F bayonet** – standard Nikon F lens adapter, preserves 46.5 mm back focal distance.

Attaching camera head to telescope mount

C1+ camera heads are equipped with “tripod” thread (0.25”) as well as four M4 threaded holes on the bottom side of the camera head.

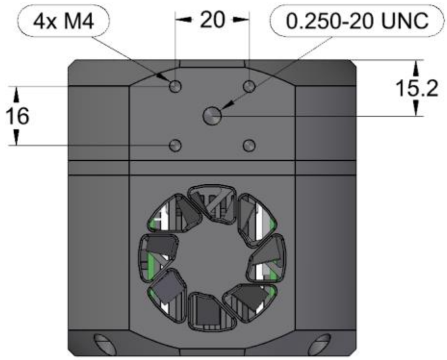


Figure 22: Threaded mounting holes on the camera head bottom side

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

Moravian Camera Ethernet Adapter

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

Figure 24: The Camera Ethernet Adapter with two connected cameras

Adjusting of the telescope adapter

All telescope/lens adapters of the C1+ 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.

The camera adapter base is 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.

Figure 25: Adjusting of the "pulling" screw

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 least 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.

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.

- C1+ camera adapters are not mounted directly on the camera head. Instead, a tilting adapter base, holding the circular spring, is always used.
- 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.

Figure 26: External filter wheels are already designed to for adjustable telescope adapters

Camera Maintenance

The C1+ 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 C1+ camera cooling is designed to be resistant to humidity inside the CMOS sensor chamber. When the temperature decreases, the copper cold finger crosses freezing point earlier than the sensor 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 CMOS 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 least one or two hours at temperature between 120 and 140 °C.

The silica-gel used in C1+ 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 27: Silica-gel container is accessible from the camera back side

Exchanging the silica-gel

C1+ cameras employ the same desiccant container like the larger C1x, C2, C3 and C4 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 28: Desiccant is held inside container by perforated cap

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 is not supplied with the camera, they are supplied only as optional accessory.

Figure 29: Optional cap, standard container, and the tool-less variant of the container

Changing the telescope adapter

Changing of the C1+ camera telescope adapter depends on whether the camera is equipped with C1 compatible adapter of C2 compatible adapter.

Changing the C1 compatible adapter

C1 compatible adapters are simply screwed into the adapter base. Replacing of the adapter needs only to unscrew the original extension adapter and screw in the new one.

Changing the C2 compatible adapter

While in principle the C1+ camera allows usage of C2 adapters through the C2 compatible base, in reality C2 adapters are used only with the External Filter Wheels.

Adapters are attached to External Filter Wheel 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 External Filter Wheel adapter base, 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 30: Replacing the C1 compatible telescope adapter