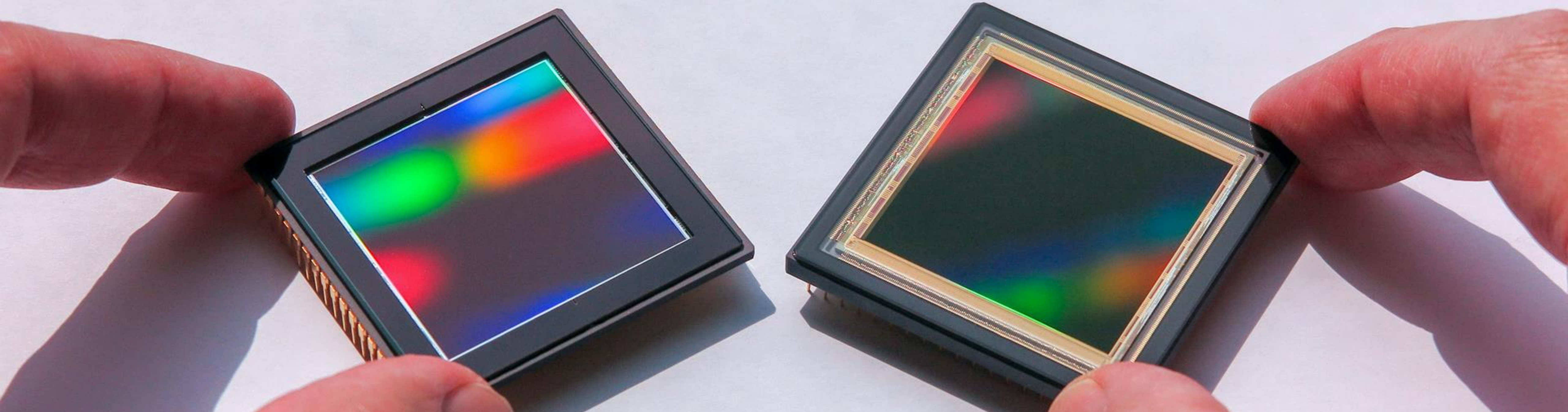
CCD versus CMOS



Pavel Cagaš (pc@tcmt.org)

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November 7th, 2020

What are differences between CCD and CMOS?

- The **CCD** and **CMOS** abbreviations, used for two sensor types, unfortunately denote different things:
  - **Charge Coupled Device** hints the principle of sensor operation.
  - **Complementary Metal Oxide Silicon** describes the process, used to create logic cells with unipolar transistors (FET).
- The very basic mechanism of light detection is the same – photon excites silicone atoms and released electrons represent amount of captured light.
  - Everything else is different – CCD is in principle analog circuit, while CMOS digital one (it uses digital electronics manufacturing lines).

CCD

- Captured photons release electrons.
- Electrons are trapped in charge wells (pixels).
- Number of electrons increases in every charge well when pixels accumulate light.

CMOS

- Captured photons release electrons.
- Electrons charge storage capacitors (diodes in reverse direction) in pixels.
- Voltage on the capacitors increase when pixels accumulate light.

CCD

- CCD is a serial device.
  - Any pixel can be reached only by subsequent shifting of charge wells through the sensor area.
- The output is analog voltage, converted to digital number by camera electronics.
- A/D conversion is typically performed with 16-bit precision (0-65535).

CMOS

- Individual pixels can be addressed (like memory cell).
- Voltage is converted to digital number inside the sensor, typically using multiple A/D converters.
- Resolution is between 8 and 12 bits (0-255 to 0-4095).
  - Rarely 14 bits or even 16 bits.
- Output is fast digital bus.

CCD (dis)advantages

- (-) Slow read
- (±) Sensitivity
- (+) Greater dynamic range (large pixel area)
- (-) Higher read noise
- (+) Electro-luminescence can be completely eliminated
- (-) Cosmetic defects (bad columns, …)

CMOS (dis)advantages

- (+) Very fast read
- (±) Sensitivity
- (-) Lower dynamic range (small pixel area)
- (+) Lower read noise
- (-) Artifacts in images (electro-luminescence, …)
- (+) Without bad columns

CCD (dis)advantages

- (+) CCD is only passive piece of silicon during exposure
- (+) Minimal thermal loss $\Rightarrow$ better cooling $\Rightarrow$ lower dark current
- (-) CCD is more and more rare and exotic technology

CMOS (dis)advantages

- (-) CMOS is continuously (and very fast) operating digital circuit
- (-) High thermal losses $\Rightarrow$ worse cooling $\Rightarrow$ greater dark current
- (+) Next development of CMOS image sensors attracts huge investments of giant companies

Brief history of commercial CCD sensors

- Many companies with experience in semiconductors and TV technology started CCD sensor development:
  - **Texas Instruments** (TC211 – ST4, TC241 – ST6, TC245 – “Cookbook camera”, …)
  - **Sony** (ICX series in cameras of various manufacturers, e.g. G0/G1)
  - **Kodak** (KAF-040x – ST7/G2-0400, KAF-160x – ST8/G2-1600, KAF-3200 – ST10/G2-3200, …)
  - **Phillips**
- “Market consolidation” left only 2 manufacturers:
  - Sony – terminated manufacturing of CCD sensors in 2016
  - Kodak – despite popular CCD sensor portfolio, Kodak was too burdened with classical film manufacturing and did not survive digital transformation

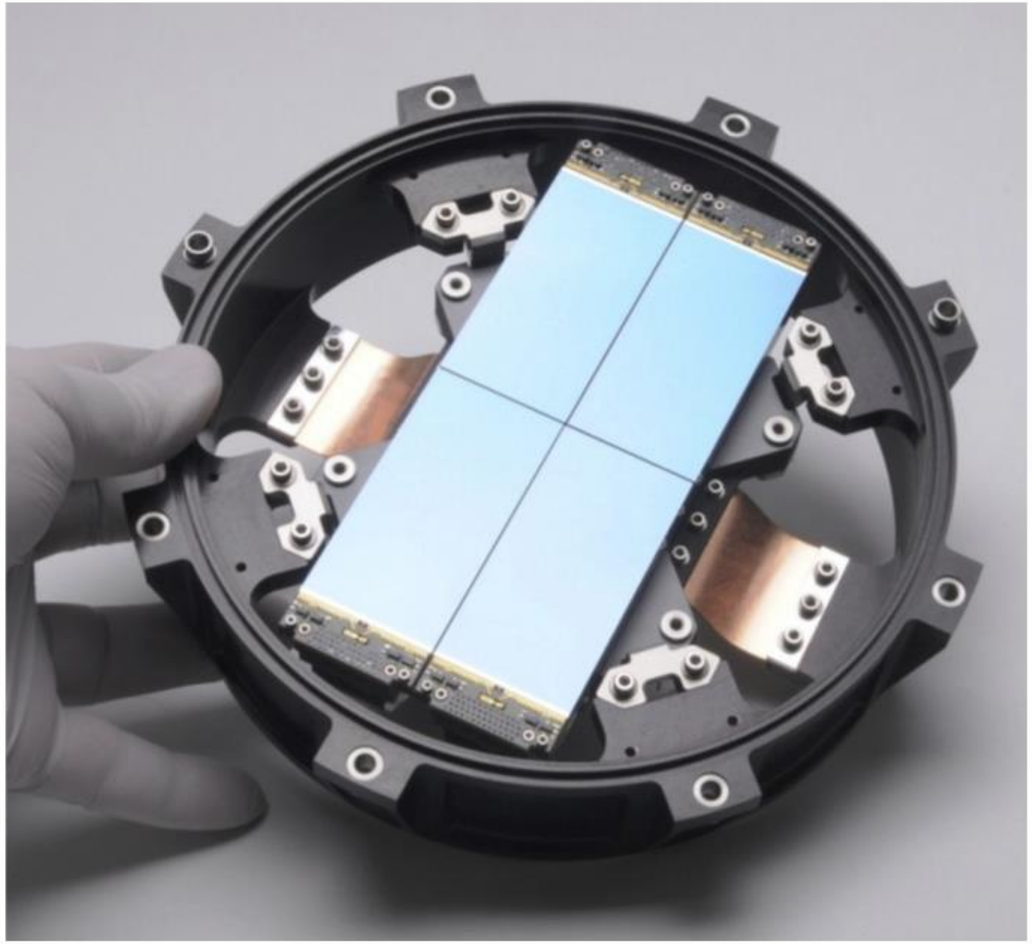
End of commercial CCD manufacturing

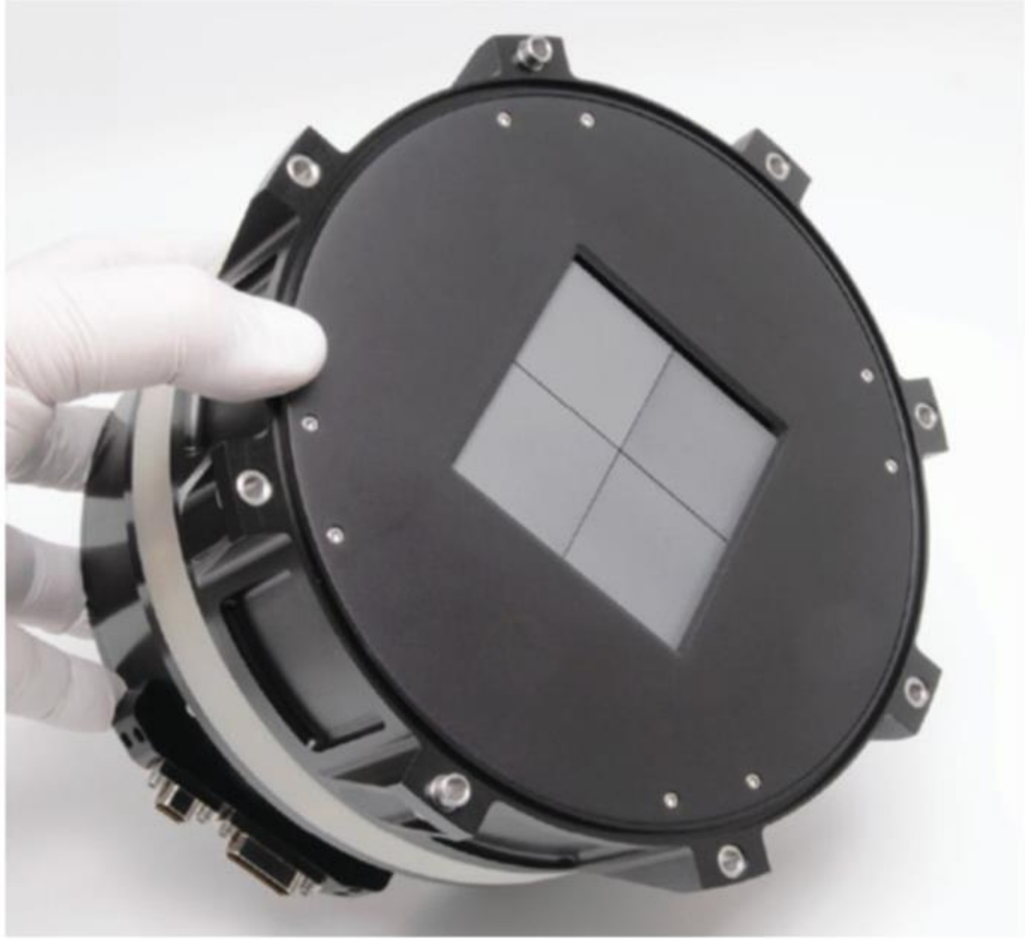
- At the edge of **Kodak** bankruptcy, CCD manufacturing is split into daughter company **Truesense Imaging** in 2011
  - Truesense Imaging product cover all CCD KAF and KAI sensors
- **OnSemiconductor** buys Truesense Imaging in 2014
  - This transaction is the beginning of the end of commercial CCD sensors
  - Cooperation with OnSemi is tremendously difficult, the company acts only through distributors, direct relations with customers is impossible, …
  - OnSemi handles CCDs like “unwanted baby”, investments into next development and CCD technology evolution is literally zero, OnSemi only exploits existing CCD lines while they bring profit
  - When the existing CCD sensors become more and more outdated, OnSemi terminates manufacturing in 2020

CMOS sensors replace the CCD ones, with the exception of hi-end research projects

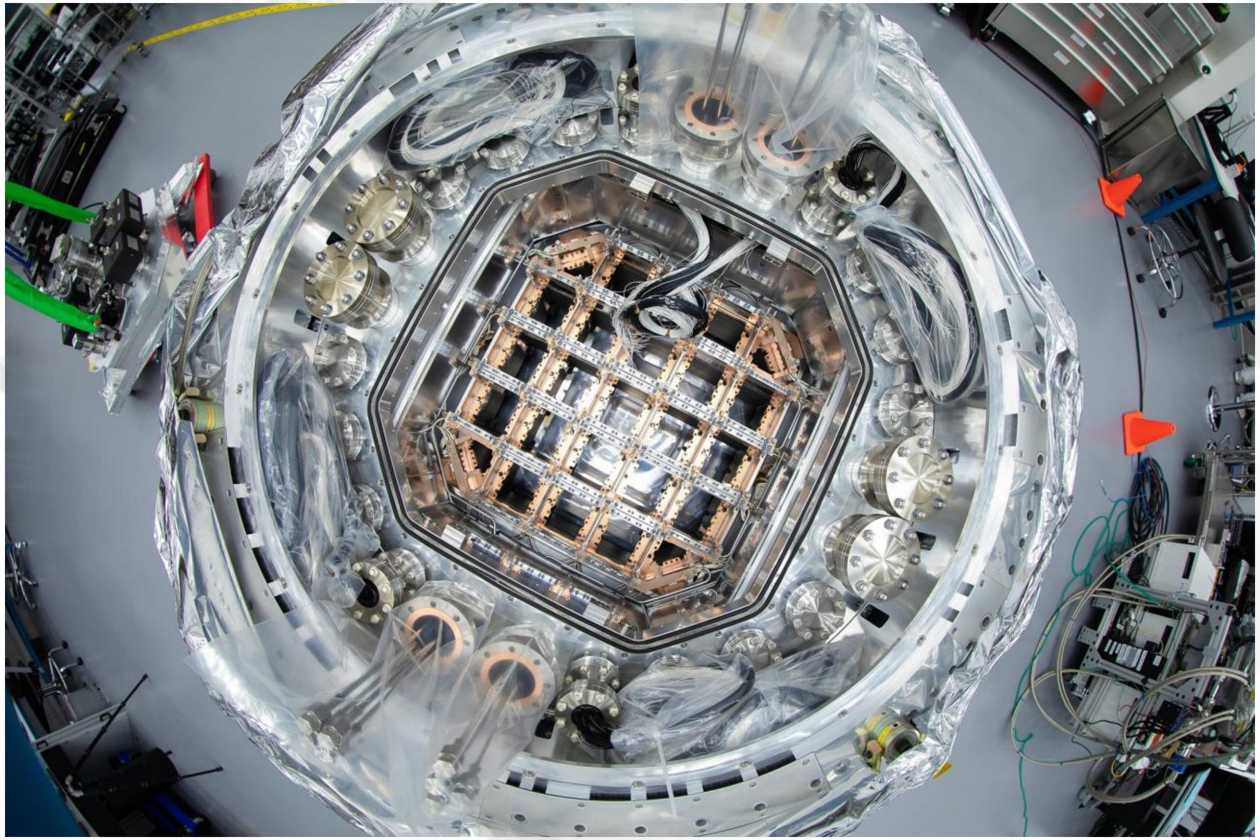
- In short “CCD is better for research, CMOS for astro-photography”
- But the debate “**CCD vs. CMOS**” become **pointless**, the future of the silicone image sensors in the CMOS technology only
- CCD is still used for hi-end research projects
  - Giant surface telescopes
  - Space telescopes
  - …
- CCD is manufactured only in very low numbers, often in university prototype labs etc.
  - The price of these sensors is “astronomical”, out of the reach of amateur astronomers

CCD sensors of the TESS cameras





3.2 GPx CCD camera of the Vera Rubin Observatory telescope



Comparison of new CMOS cameras C1, C1+ and C2

Camera series	C1	C1+	C2
Camera front cross-section	57 × 57 mm	78 × 78 mm	114 × 114 mm
Camera length (without adapter)	49 mm	80 mm	65 mm
Camera weight	215 g	675 g	1000 g
Power source	USB only	USB and 12 V DC	12 V DC only
Mechanical shutter	No	No	Yes
Active sensor cooling	No	Yes (12V DC)	Yes
Internal filter wheel	No	No	Optional
External filter wheel	No	Optional (12V DC)	Optional
Autoguider port	Yes	Yes	No

Gx versus Cx: sensor dimensions

- G2-0400:
  - 6.9 × 4.6 mm
- G2-1600:
  - 13.8 × 9.2 mm
- G2-3200:
  - 14.9 × 10.0 mm
- G2-8300:
  - 18.1 × 13.7 mm
- G2-4000:
  - 15.2 × 15.3 mm

- C1-1500:
  - 5.02 × 3.75 mm
- C1/C1+/C2-3000:
  - 7.12 × 5.33 mm
- C1/C1+/C2-5000:
  - 8.50 × 7.09 mm
- C1/C1+/C2-12000:
  - 14.19 × 10.38 mm
- C1+/C2-7000:
  - 14.47 × 9.94 mm

Gx versus Cx: pixel size and capacity

- G2-0400/1600:
  - 9.0 µm, 100 000 e-
- G2-3200:
  - 6.8 µm, 55 000 e-
- G2-8300:
  - 5.4 µm, 25 000 e-
- G2-4000:
  - 7.4 µm, 40 000 e-
- Cx-1500/3000/5000/12000:
  - 3.45 µm, 11 000 e-
- Cx-7000:
  - 4.5 µm, 26 000 e-

Gx versus Cx: digitization bit depth

- Gx: 16 bits (0 .. 65535)

- Cx: 12 bits (254 .. 4094)
  - Value 4095 is not returned by sensors
- Binning implemented in software by adding pixels
  - 2×2: (1016 .. 16376)
  - 3×3: (2286 .. 36864)
  - 4×4: (4064 .. 65504) (~16 bit)

Gx versus Cx: read noise

- G2-0400/1600:
  - 13 e- RMS
- G2-3200:
  - 8 e- RMS
- G2-8300:
  - 8 e- RMS
- G2-4000:
  - 7 e- RMS

- Cx-1500/3000/5000/12000:
  - 2.15 e- RMS (binning 1×1)
  - 4.30 e- RMS (binning 2×2)
- Cx-7000:
  - 5.35 e- RMS (binning 1×1)
  - 10.70 e- RMS (binning 2×2)
- Signal in 2×2 binning grows 4 times, but read noise only 2 times

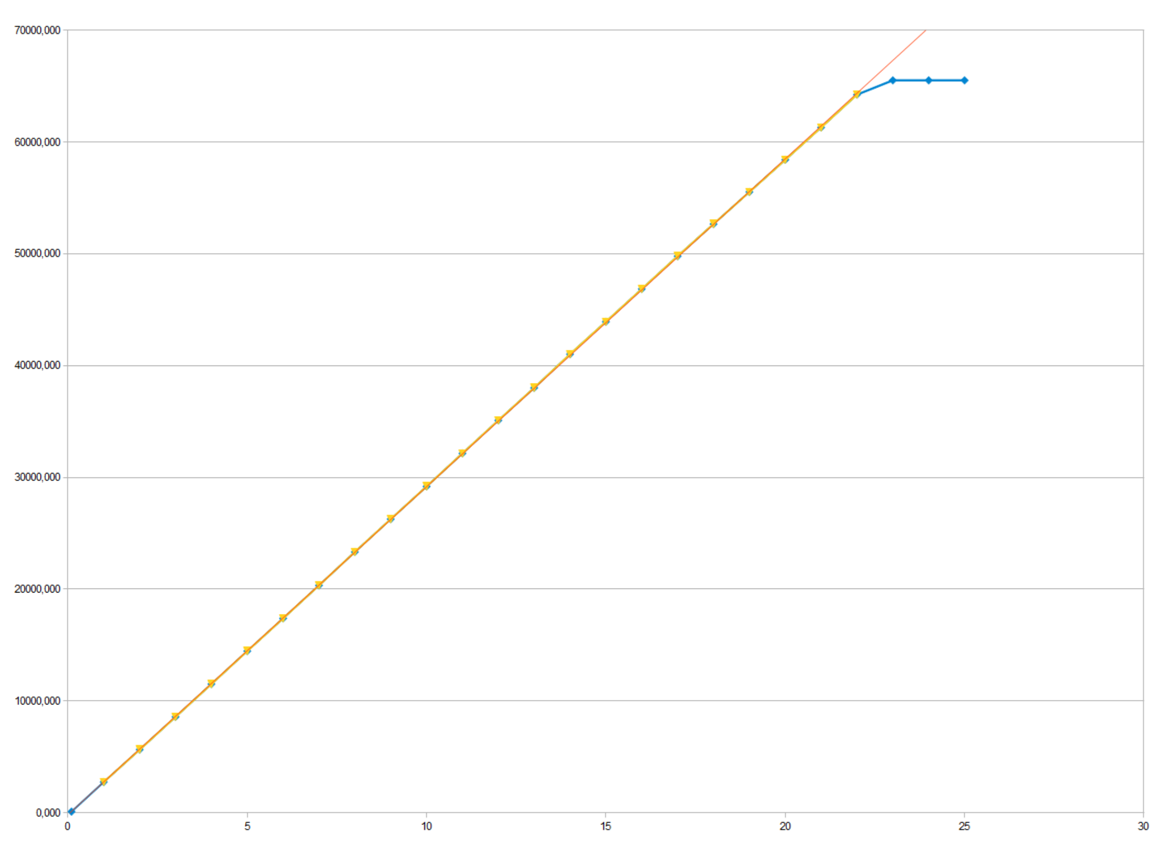
Gx versus Cx: maximum quantum efficiency

- G2-0400/1600:
  - 80%
- G2-3200:
  - 85%
- G2-8300:
  - 53%
- G2-4000:
  - 55%

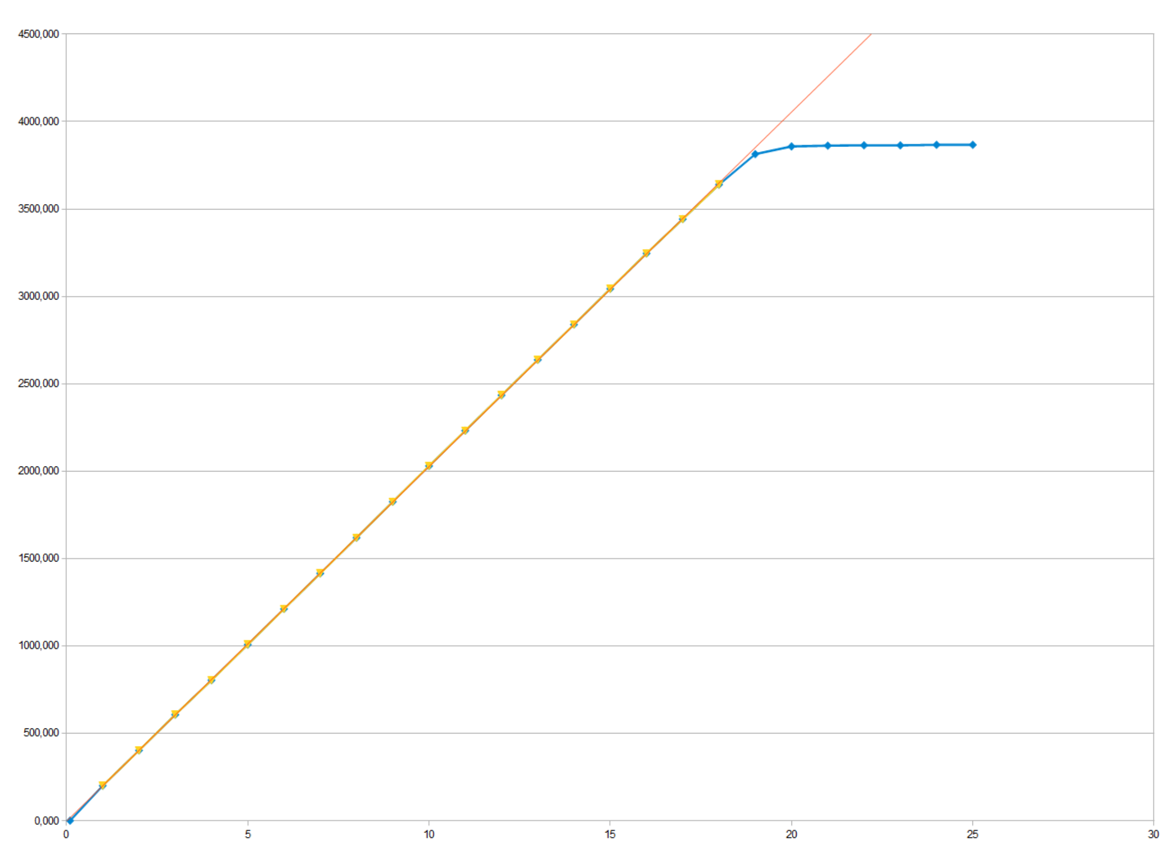
- Cx-1500/3000/5000/12000:
  - 67%
- Cx-7000:
  - 68%
- Signal/noise depends on dominant source of noise:
  - **Read noise** prevails – CMOS S/N better than CCD
  - **Sky background** noise prevails – CMOS S/N worse than CCD

Gx versus Cx: linearity

- G2-1600 (KAF-1603ME)

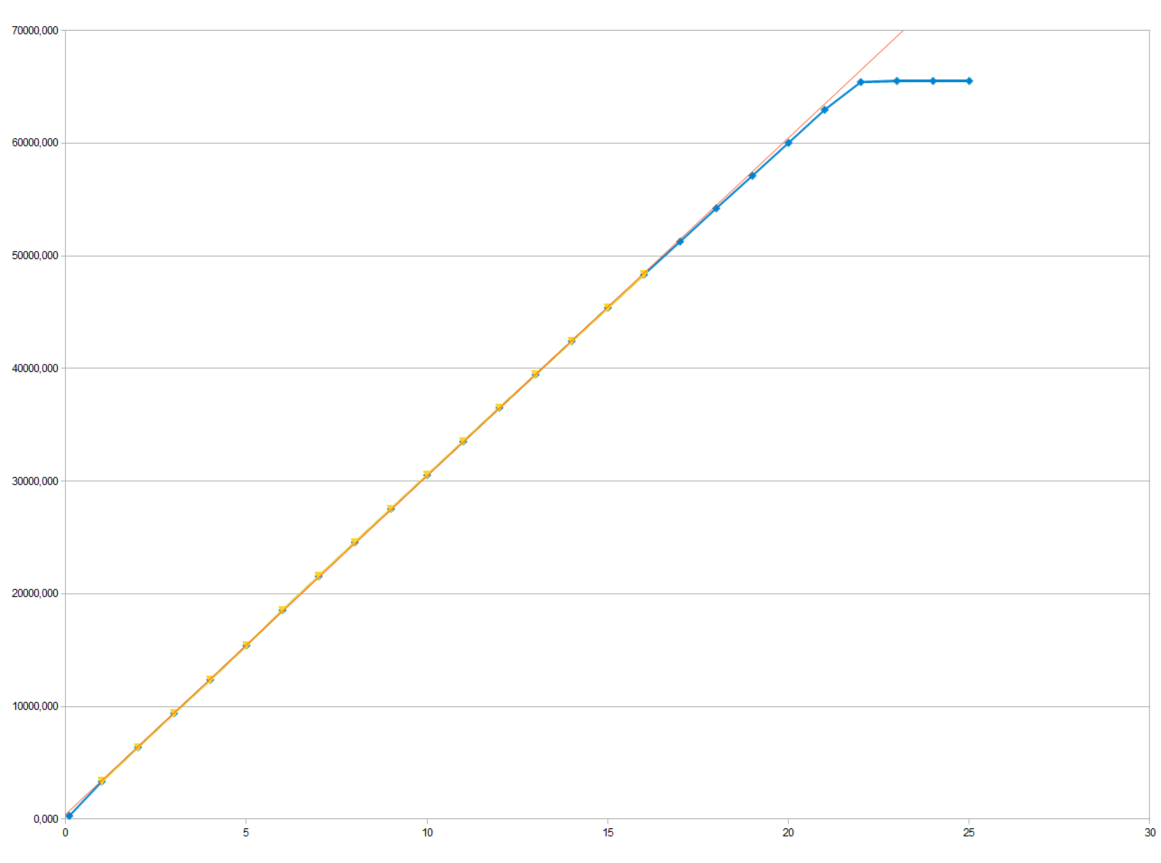


- C2-3000A (IMX525)

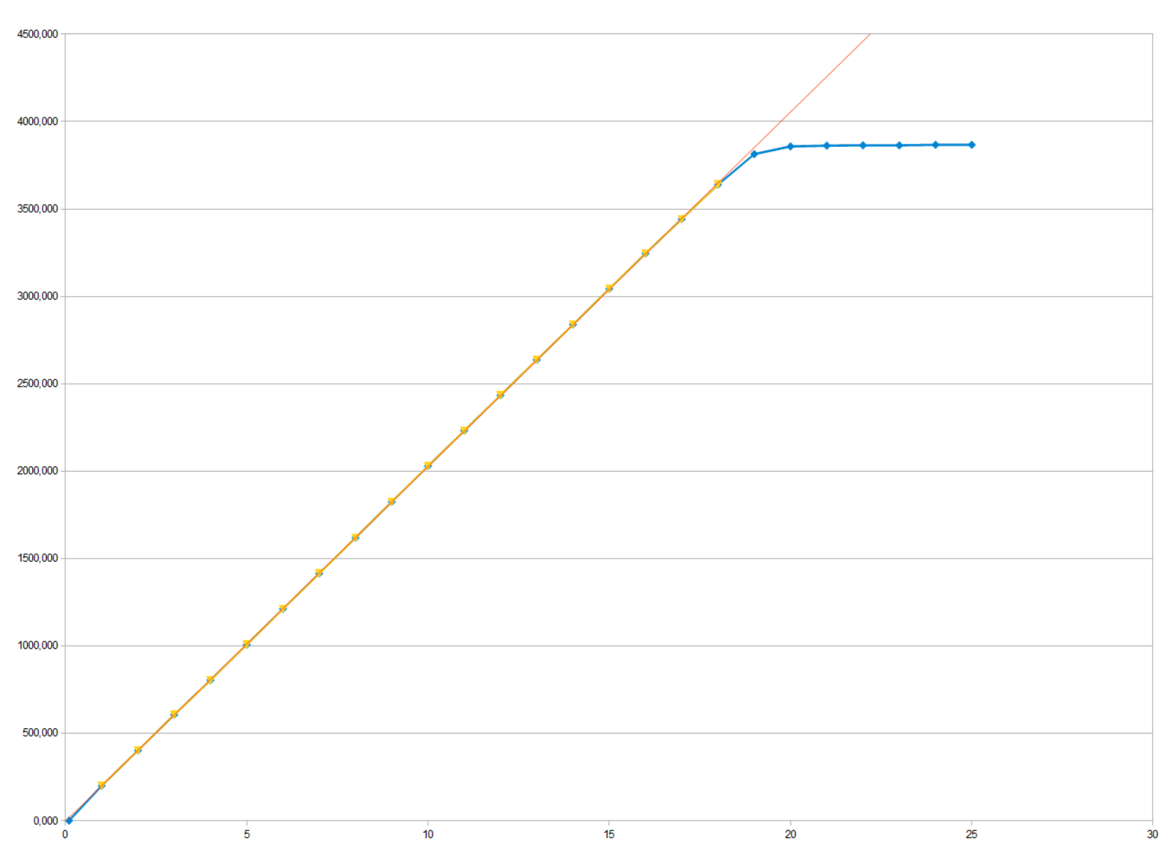


Gx versus Cx: linearity

- G2-8300 (KAF-8300)

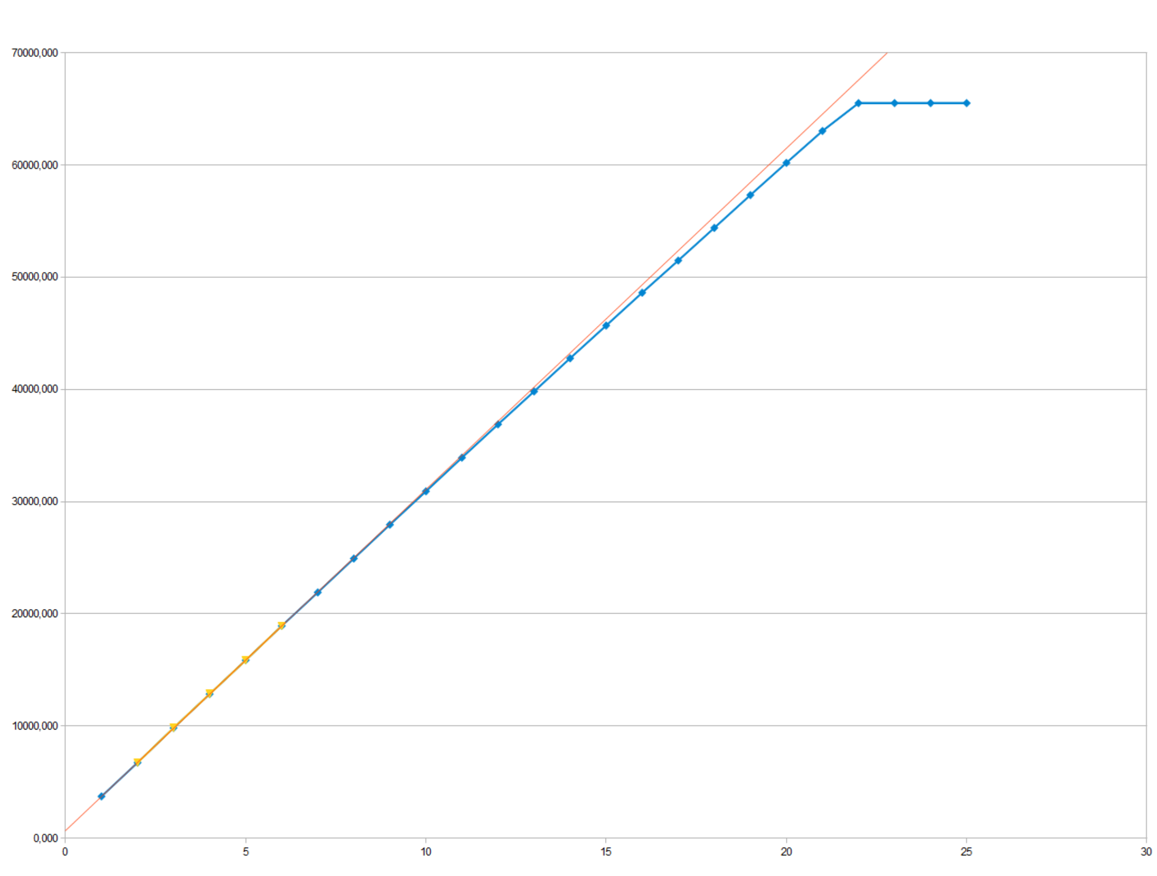


- C2-3000A (IMX525)

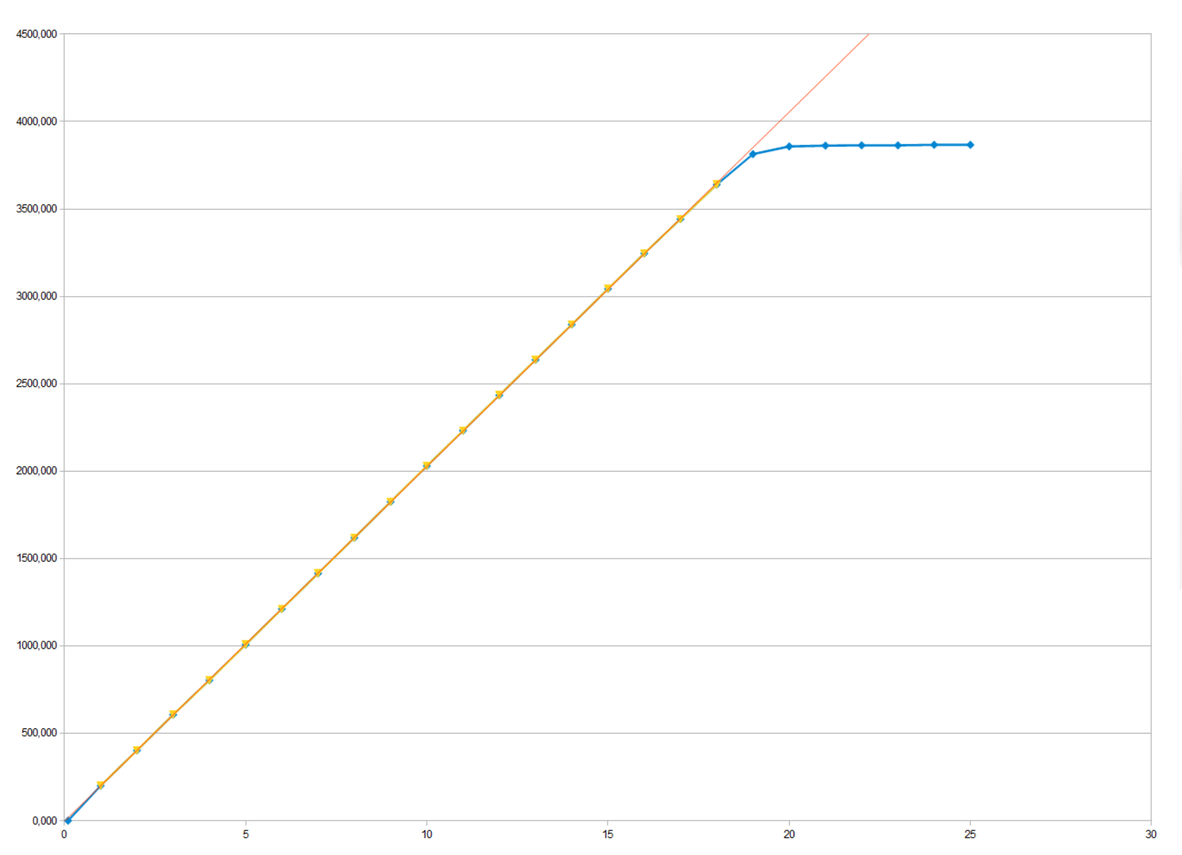


Gx versus Cx: linearity

- G3-16200 (KAF-16200)



- C2-3000A (IMX525)



NGC7635 “Bubble” nebula

(C2-12000, Martin Myslivec)

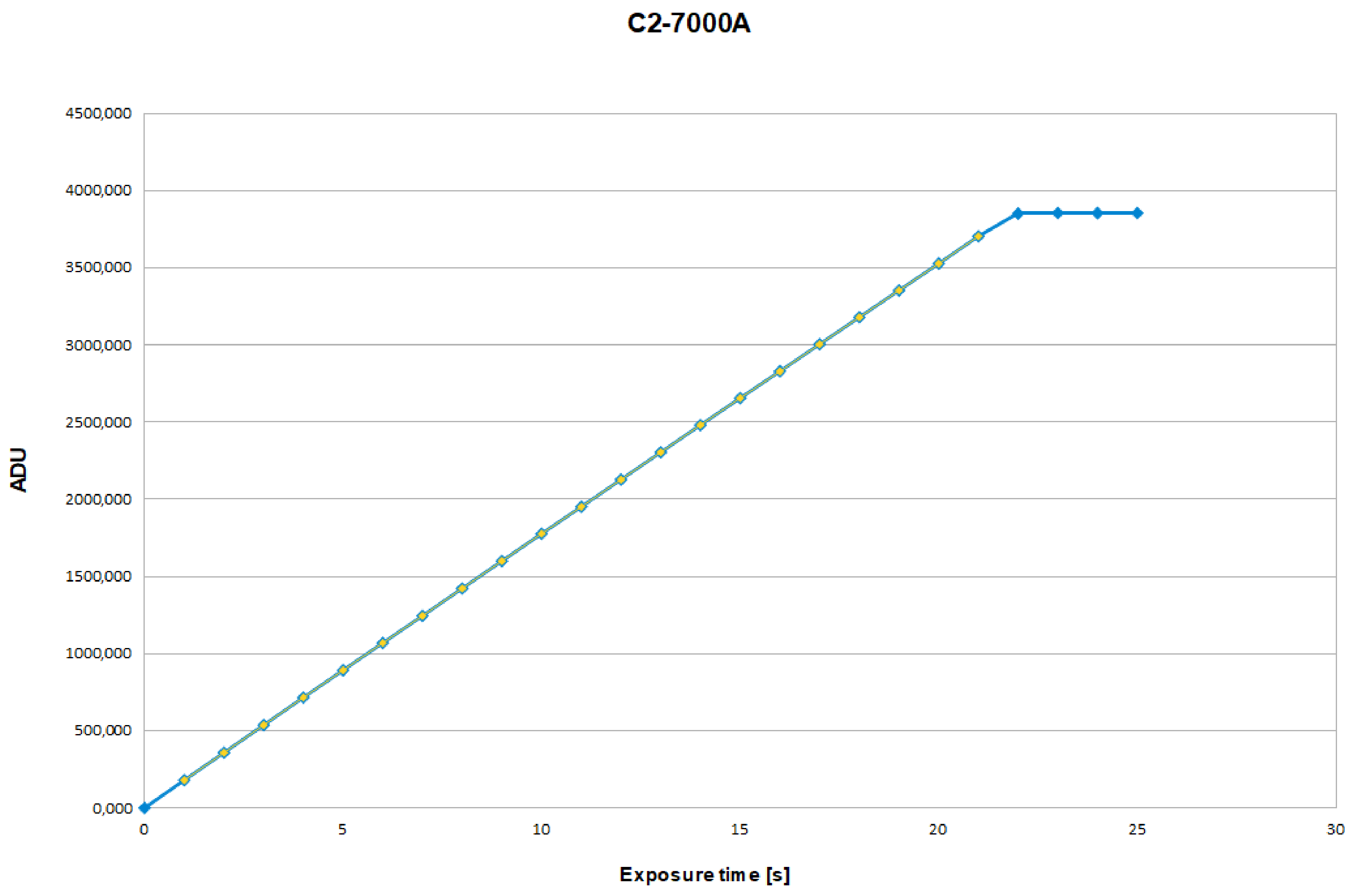
M82 “Cigar” galaxy

(C2-12000, Martin Myslivec)

C2-7000 (C1+7000) – G2-1600 replacement for photometric applications?

	G2-1600	C2-7000	C2-7000 (binning 2×2)
Sensor	CCD KAF-1603ME	CMOS IMX428	CMOS IMX428
Number of pixels	1536 × 1024 (1.5 M)	3216 × 2208 (6.8 M)	1608 × 1104 (1.7 M)
Sensor area	13.8 × 9.2 mm	14.8 × 9.9 mm	14.8 × 9.9 mm
Pixel size	9 × 9 µm	4.5 × 4.5 µm	9 × 9 µm
Pixel capacity	100 000 e-	26 000 e-	104 000 e-
Quantum efficiency	80 %	68 %	68 %
Read noise	~13 e- RMS	~5.3 e- RMS	~10.7 e- RMS
Dynamic range (S/N)	1 : 7 692	1 : 4 905	1 : 9 720
Digitization range	16-bit (0..65535)	12-bit (0..4094)	14-bit (0..16376)
Frame download time	0.95 s (Mark II)	0.05 s (USB3)	0.05 s (USB3)
Sensor cooling	-50 °C	-42 °C	-42 °C

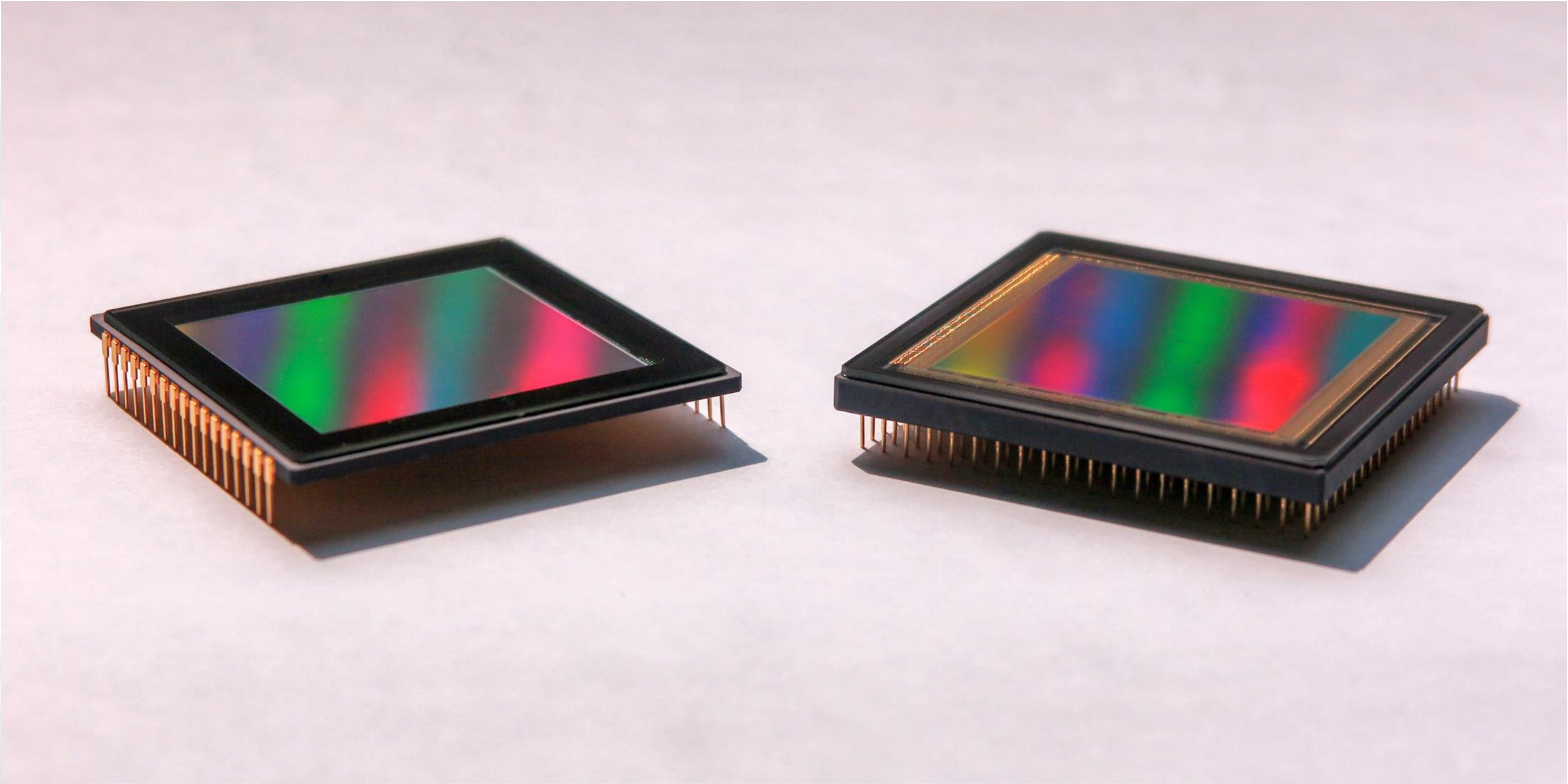
C2-7000A linearity



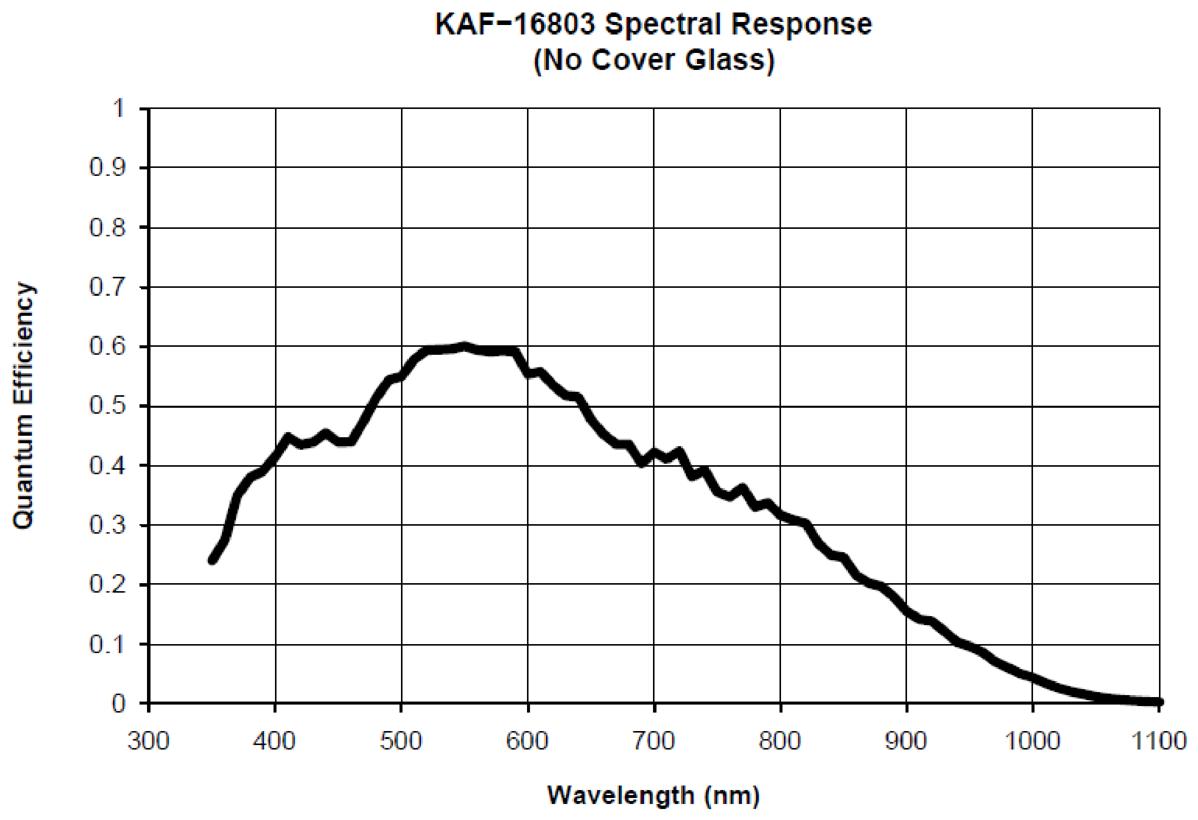
C4-16000 versus G4-16000 (CMOS versus CCD in real application)

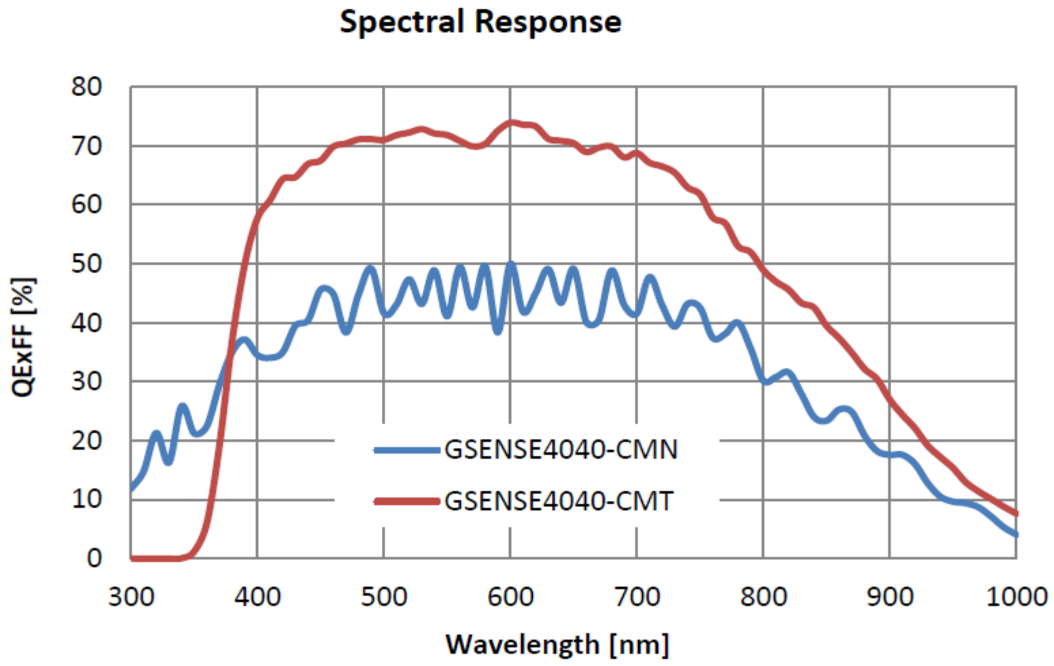
- CMOS camera **C4-16000** (GSENSE4040)
  - 4096×4096 9 µm pixels (37×37 mm)
  - 2× 12-bit ADC (combined into 16 bits)
  - Gain 0.85 e-/ADU (~55 ke-/pixel)
  - Read noise ~4 e- RMS
  - Frame download time 0.25 s
- CCD camera **G4-16000** (KAF-16803)
  - 4096×4096 9 µm pixelů (37×37 mm)
  - 16-bit ADC
  - Gain 1.6 e-/ADU (~100 ke-/pixel)
  - Read noise ~10 e- RMS
  - Frame download time 10 s

KAF-16803 (CCD), GSENSE4040 (CMOS)

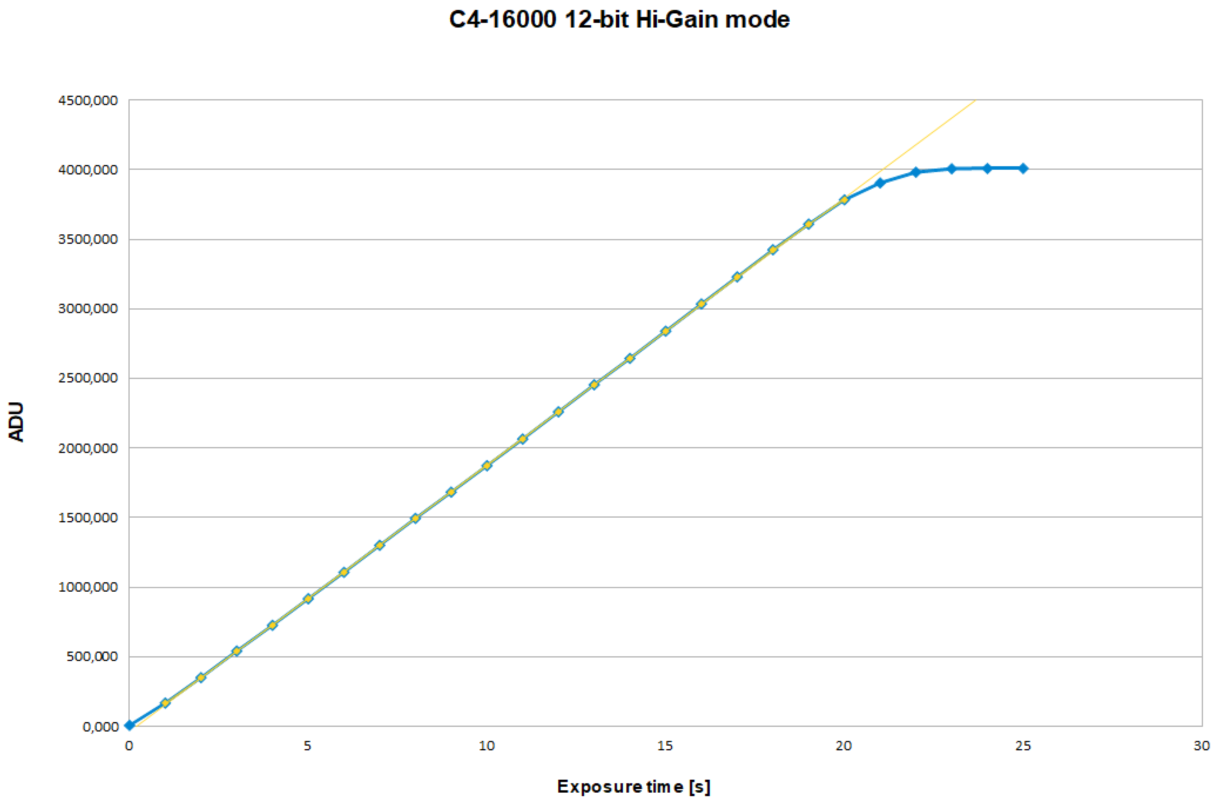


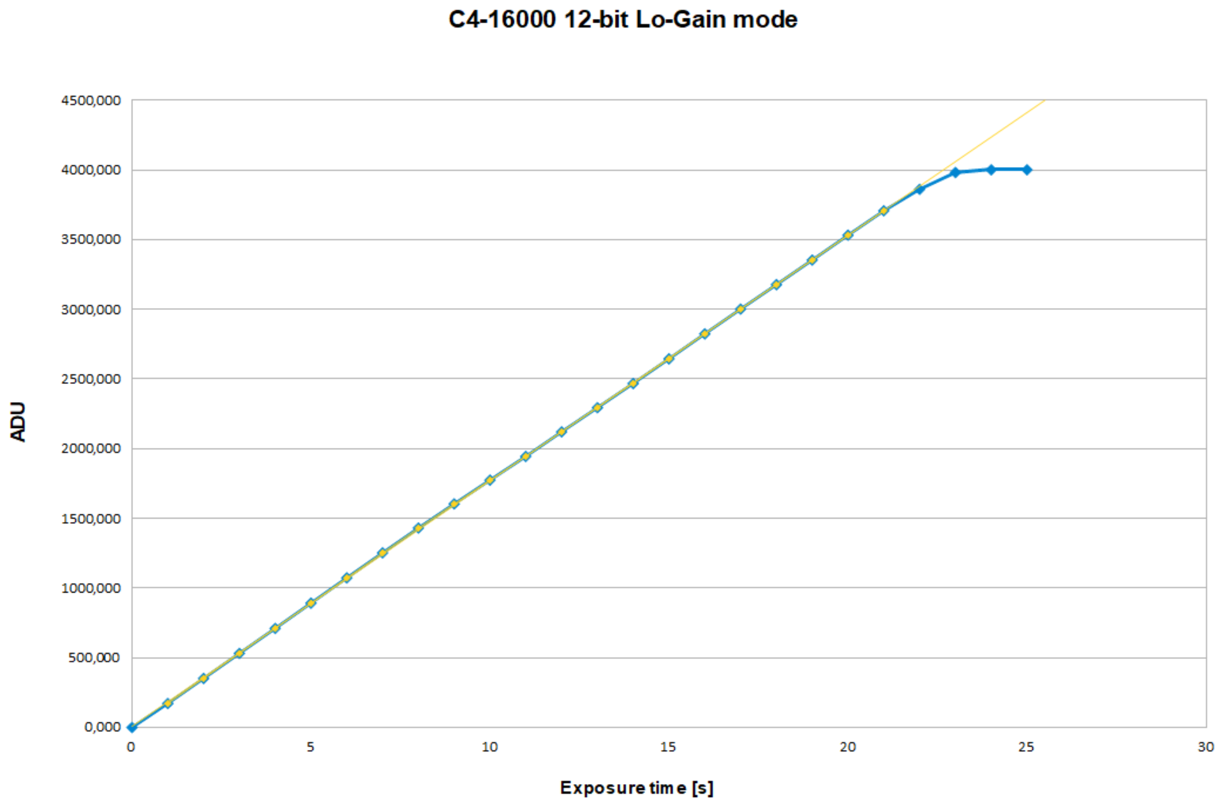
G4-16000 and C4-16000 quantum efficiency





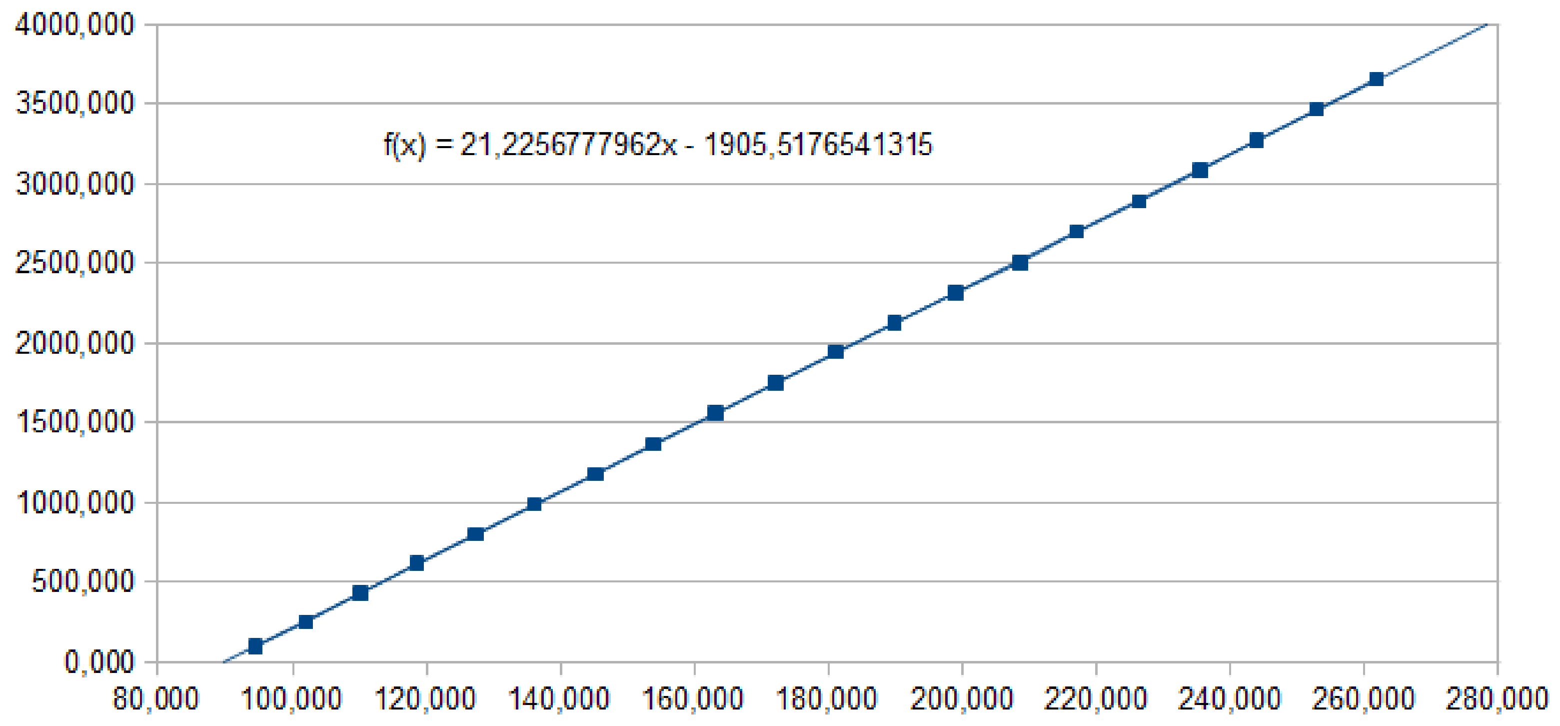
C4-16000 linearity



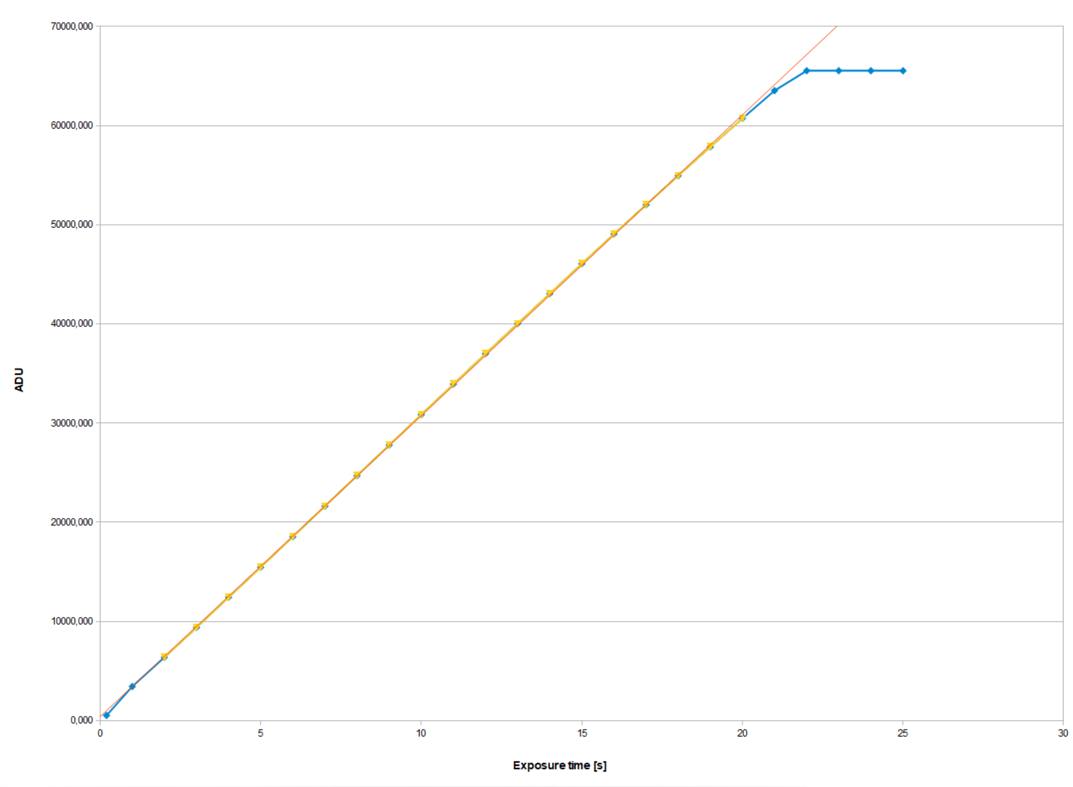


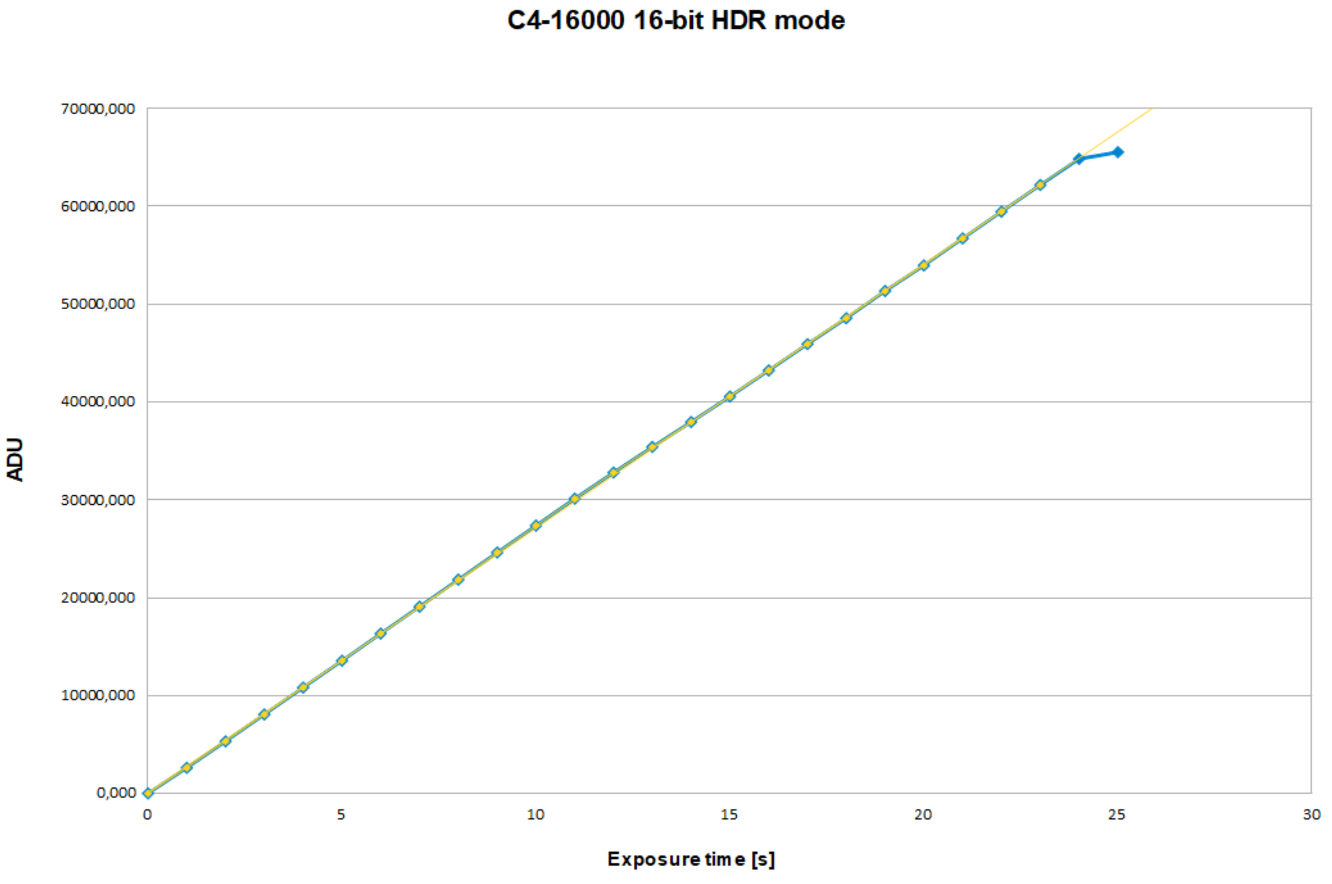
12-bit Hi-gain and Lo-gain image combination into 16-bit “HDR” image

Exp. time	Hi-gain	Lo-gain
0,00	94,136	94,442
0,25	250,747	102,006
0,50	431,229	110,227
0,75	618,546	118,650
1,00	803,371	127,419
1,25	988,554	136,126
1,50	1178,758	145,173
1,75	1368,736	153,893
2,00	1561,256	163,234
2,25	1750,518	172,061
2,50	1942,965	181,134
2,75	2129,870	189,909
3,00	2314,582	198,928
3,25	2503,835	208,506
3,50	2696,277	216,997
3,75	2890,054	226,357
4,00	3081,610	235,362
4,25	3274,547	243,882
4,50	3466,411	252,902
4,75	3660,130	261,736



G4-16000 and C4-16000 (16-bit HDR mode) linearity





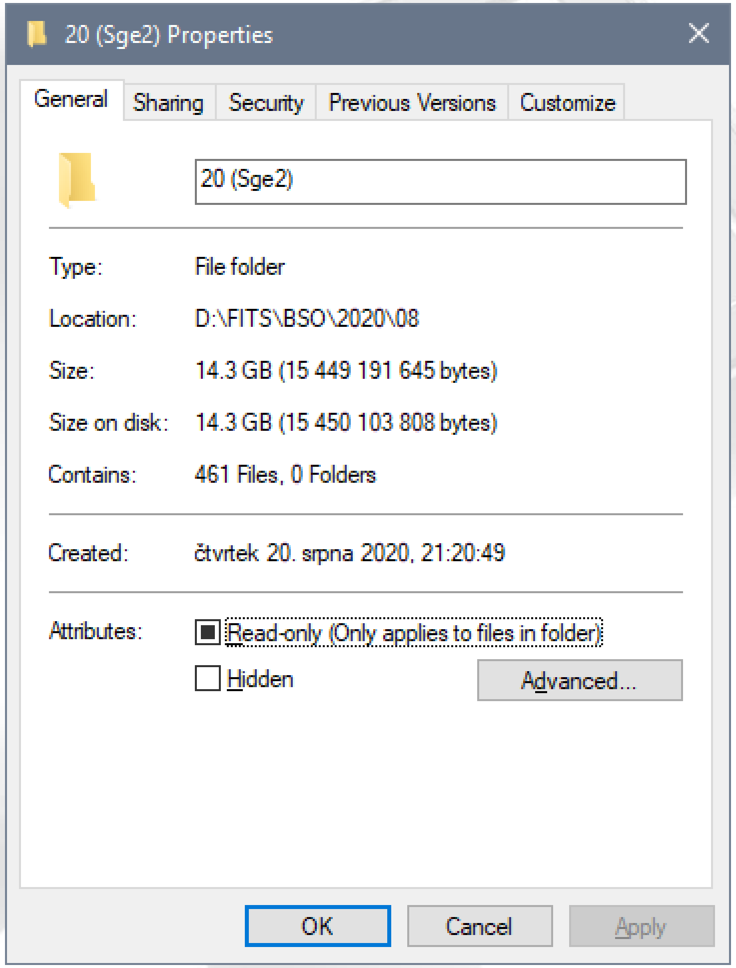
Flat Field

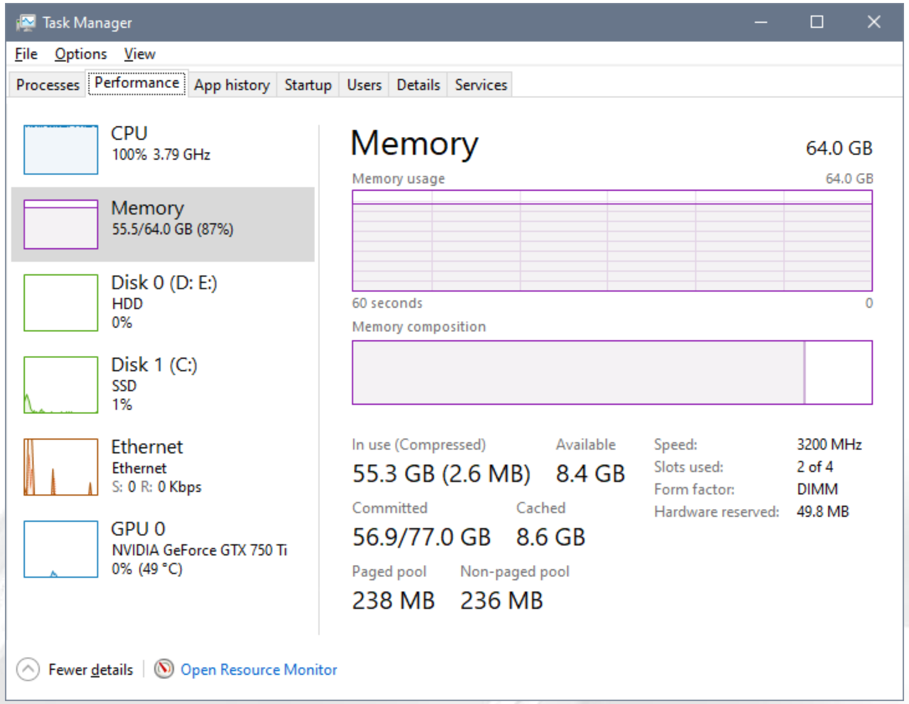
- The shortest exposure time of a Full-Frame CCD sensor is determined by the used mechanical shutter:
  - Shutter is designed to provide “equal exposure” of every sensor portion
  - Even if the shutter movement is relatively slow, (0.1s for G2, 0.2s for G3/G4 cameras), every pixels is exposed for the same amount of time
  - Bur non-uniform movement cause the shortest Flat Field exposure is 2-3s for G2 cameras and 4-6s for G3/G4 cameras
  - Flat Field could be acquired on the twilight/dawn sky only within a very short period when ~5s exposure time causes ~32k ADU signal
- Shortest exposure time of the C4-16000 is 21 μs
  - Flat Field then can be comfortably acquired anytime during daylight, or using bright artificial surfaces etc.

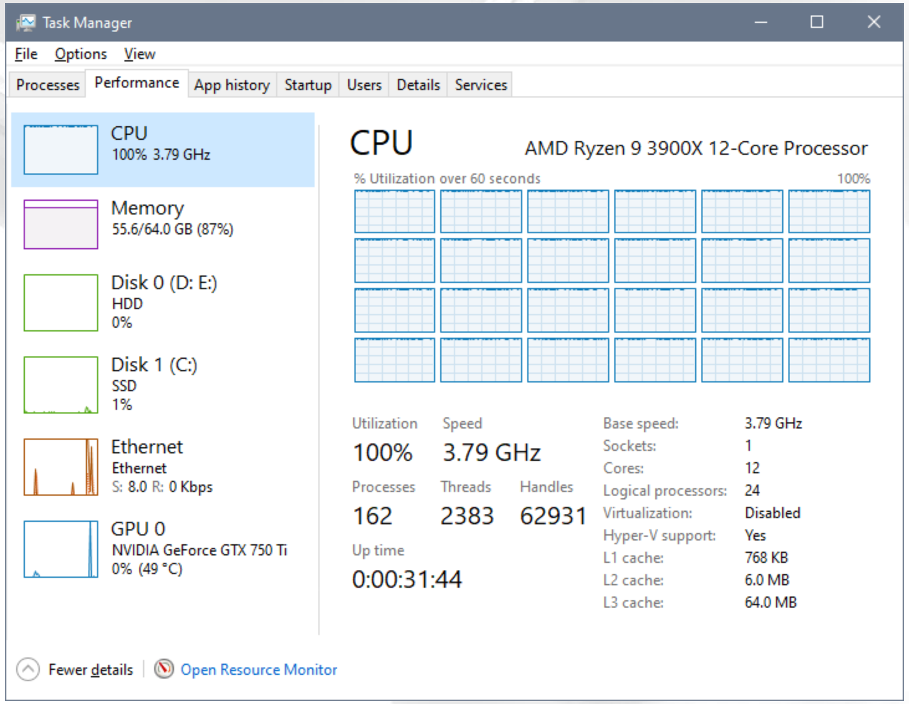
Data size

- The C4 has greater QE, 0.85 e-/ADU gain and 55ke- pixel capacity, so pixels saturate with < ½ of G4 camera exposure time
- G4-16000:
  - 90s exposure time, 10 s image download
  - Image cadence ~100 s
- C4-16000:
  - 50s exposure time, 0.25 s image download
  - Image cadence ~50 s for the same brightness of observed stars
- The result is **2-times more data** for the same run (~15GB per night)
- Also disk space requirements, necessary computer memory are doubled

PC resources requirements increase with bigger data



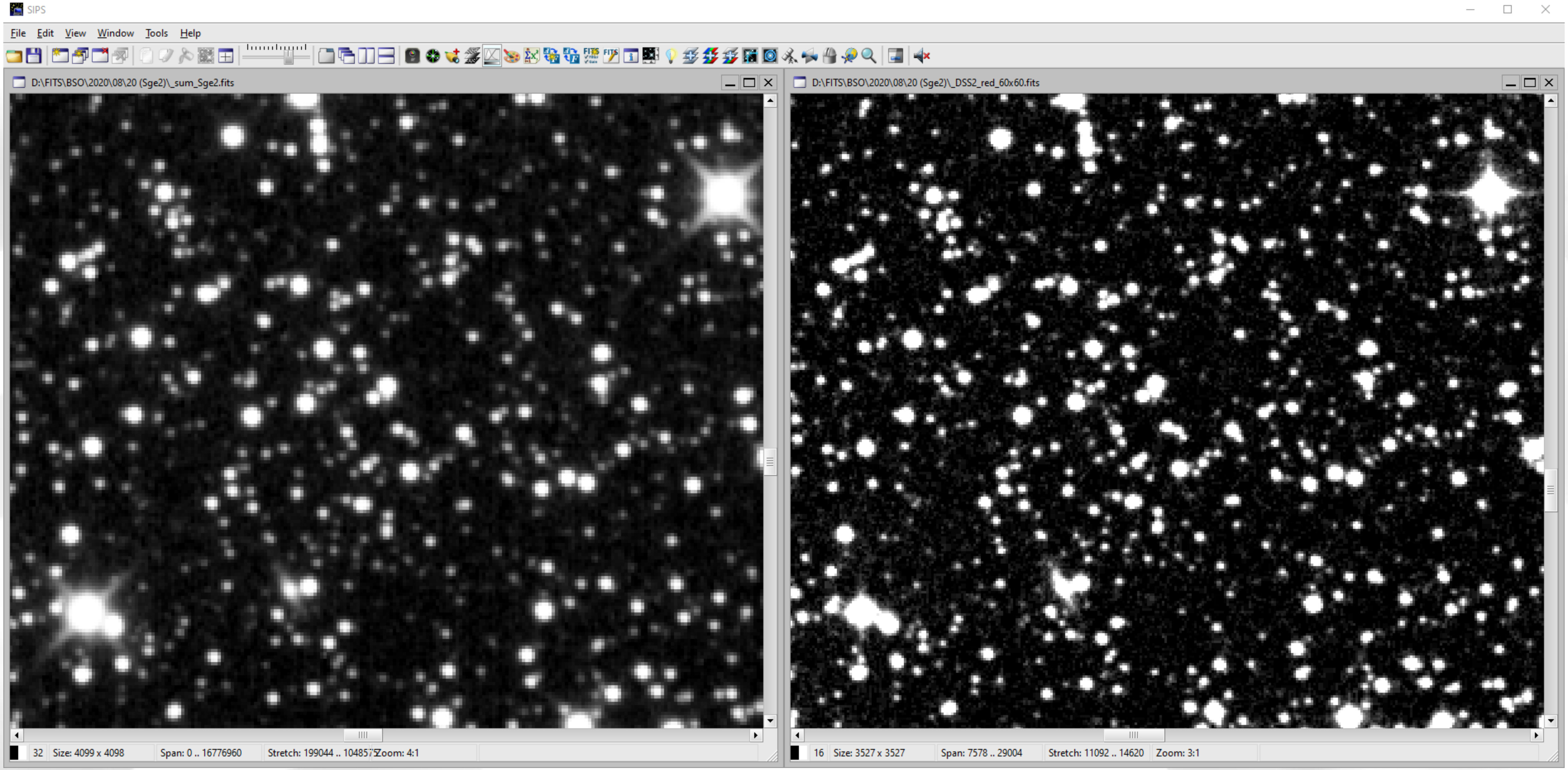


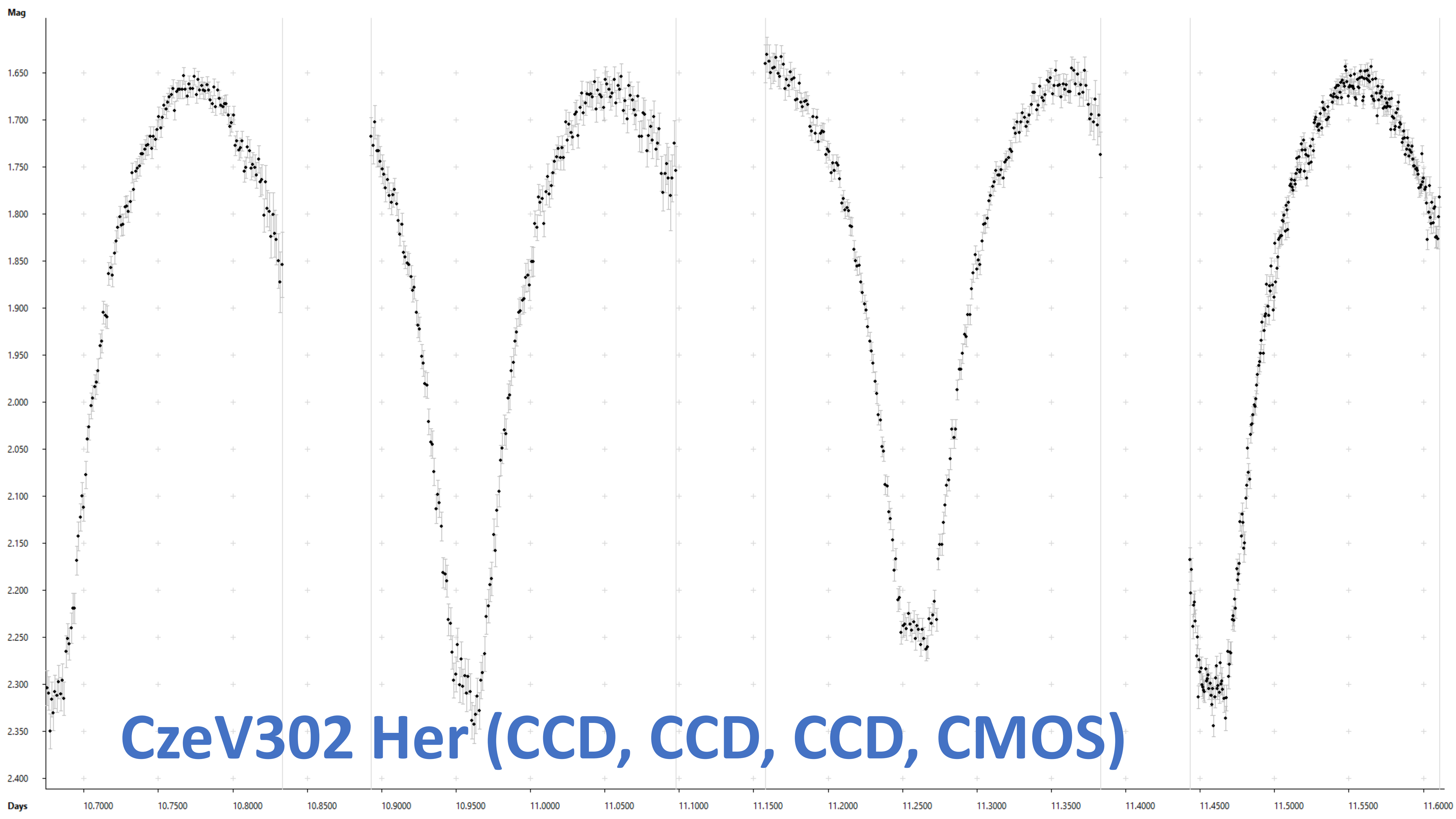


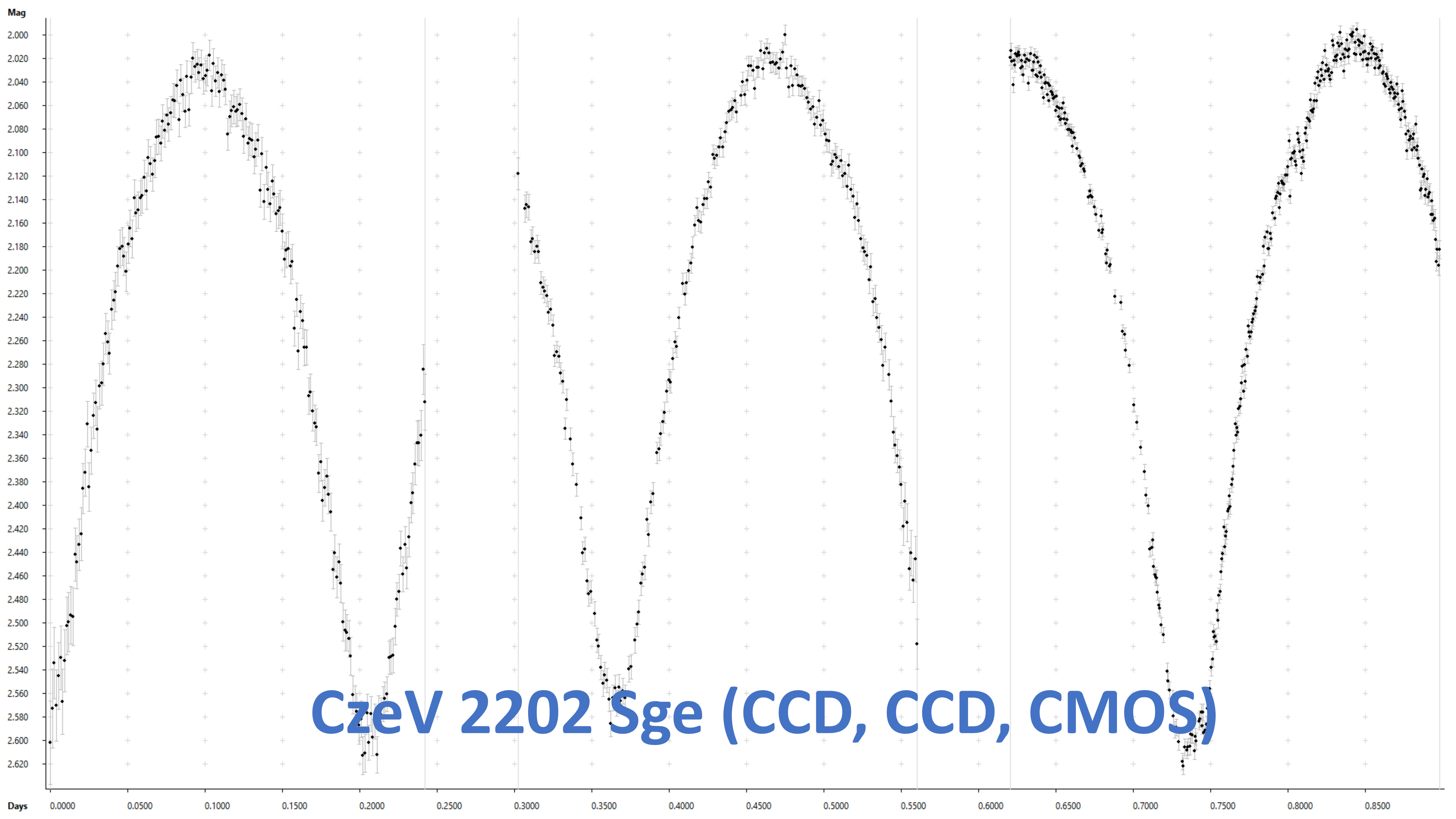
Sensor temperature (cooling efficiency)

- CCD KAF-16803 in G4-16000 is only **passive piece of silicon** while integrating light, only DC bias voltages are present
  - Thermal dissipation is minimal
  - Sensor can achieve **ΔT 50 °C under ambient temperature**
- CMOS GSENSE4040 in C4-16000 is **continuously operating**, rather fast digital circuit
  - Thermal dissipation can achieve 0.4 W
  - The same cooling, like in G4, can achieve only **ΔT 35 °C**
- Typical summer night (evening) ~28 °C
  - CCD sensor in G4-16000EC can achieve -15 or -20 °C
  - CMOS sensor in C4-16000EC hardly achieve -5 °C

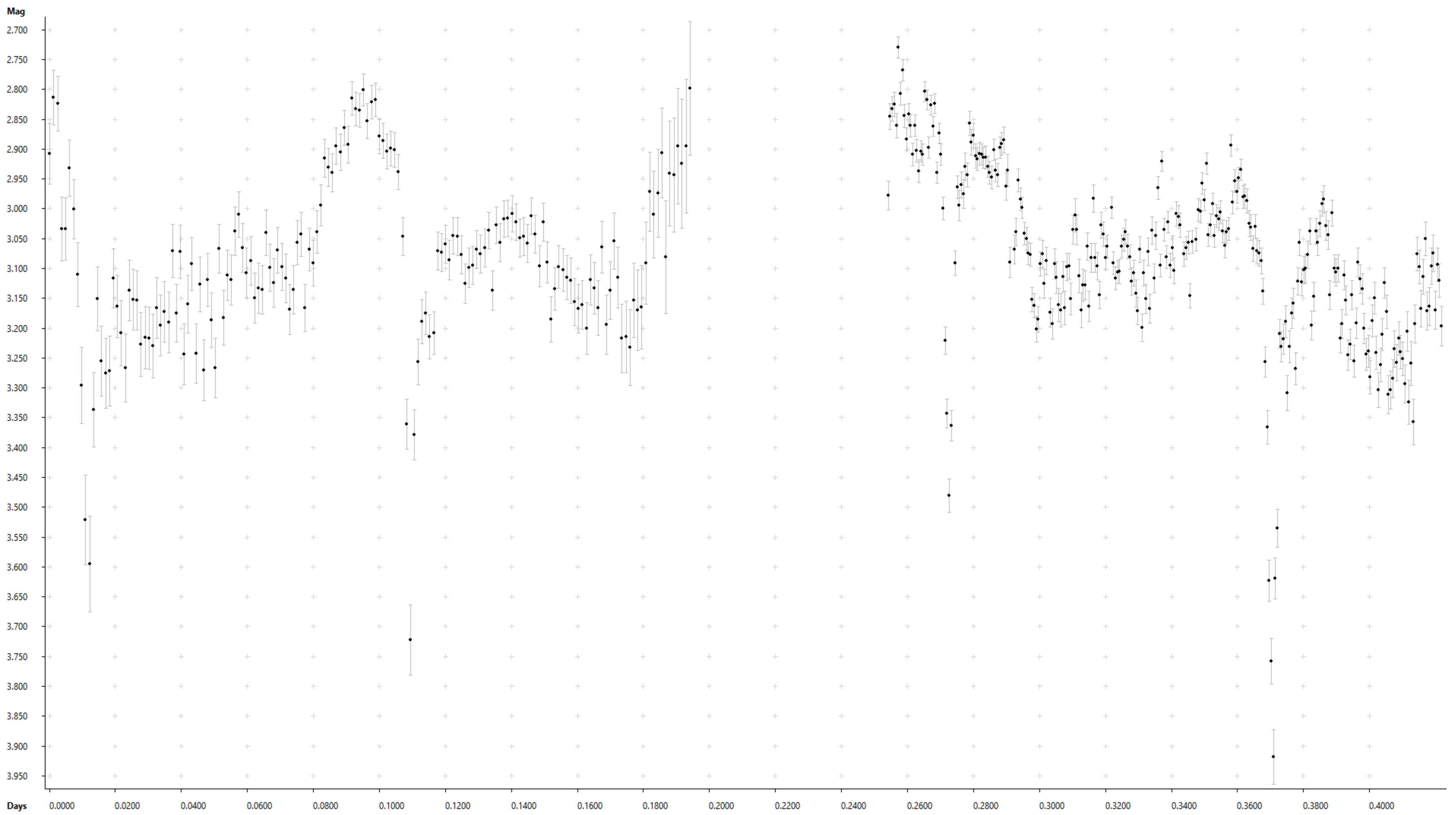
3.5 h exposure time C4-16000 vs. DSS2



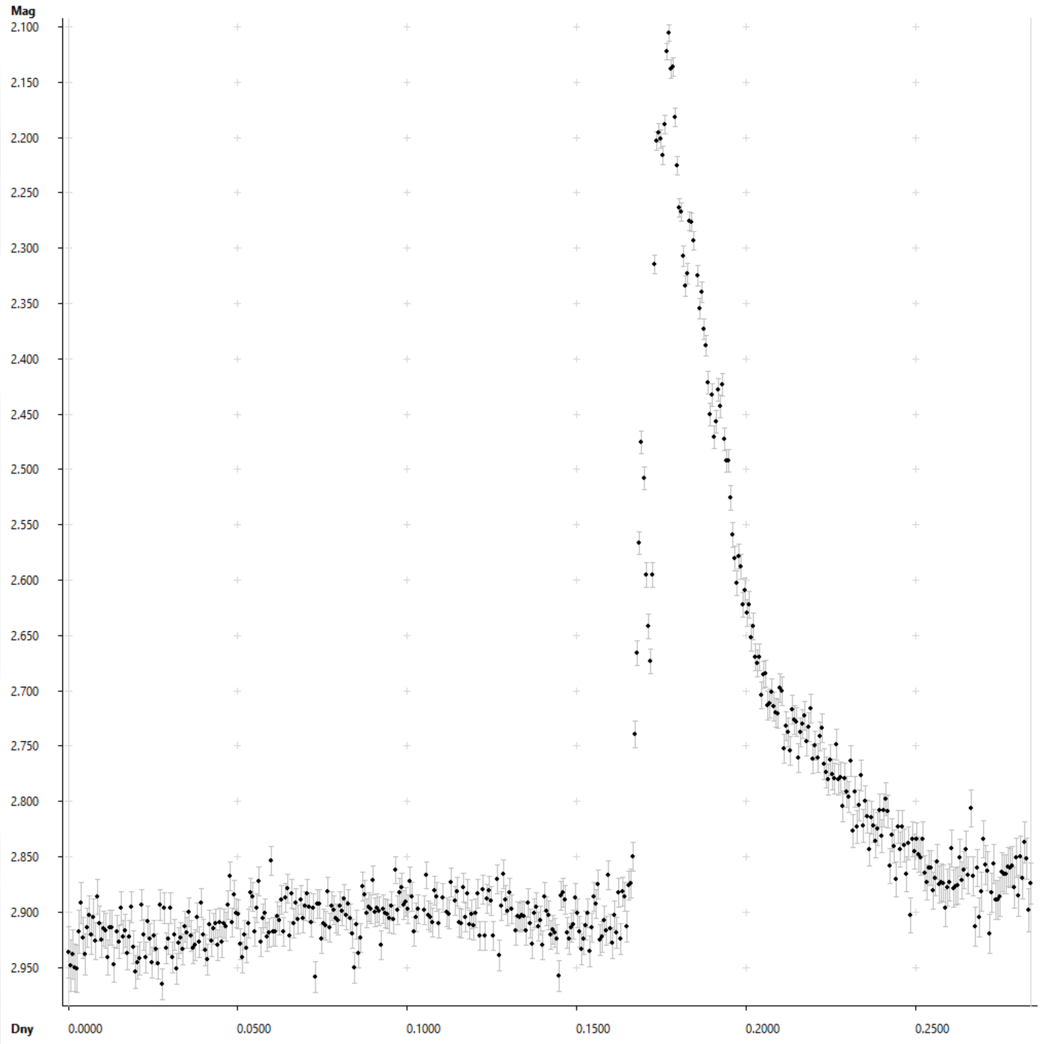

Mag
1.650
1.700
1.750
1.800
1.850
1.900
1.950
2.000
2.050
2.100
2.150
2.200
2.250
2.300
2.350
2.400
Days
10.7000
10.7500
10.8000
10.8500
10.9000
10.9500
11.0000
11.0500
11.1000
11.1500
11.2000
11.2500
11.3000
11.3500
11.4000
11.4500
11.5000
11.5500
11.6000
CzeV302 Her (CCD, CCD, CCD, CMOS)

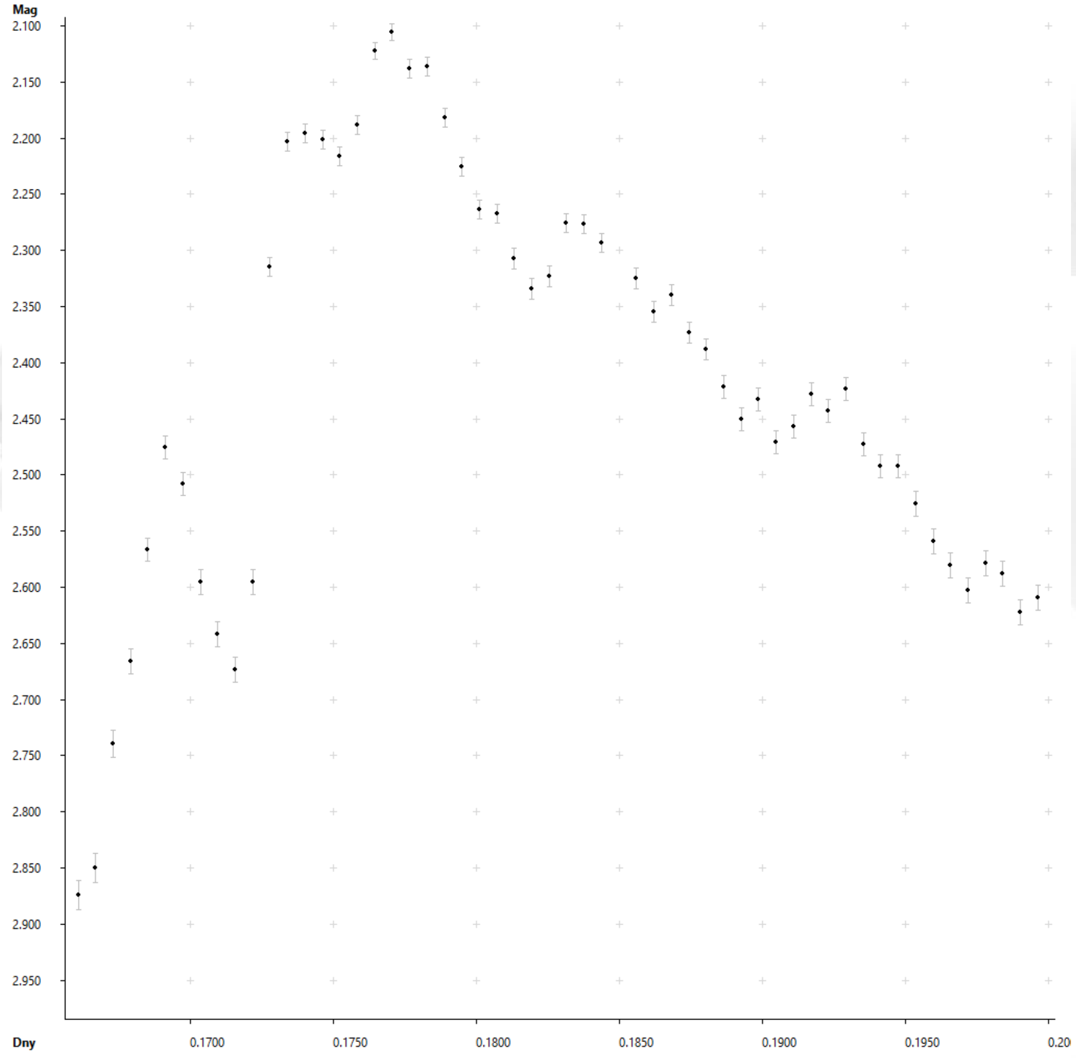

Mag
2.000
2.020
2.040
2.060
2.080
2.100
2.120
2.140
2.160
2.180
2.200
2.220
2.240
2.260
2.280
2.300
2.320
2.340
2.360
2.380
2.400
2.420
2.440
2.460
2.480
2.500
2.520
2.540
2.560
2.580
2.600
2.620
Days
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
0.4000
0.4500
0.5000
0.5500
0.6000
0.6500
0.7000
0.7500
0.8000
0.8500
CzeV 2202 Sge (CCD, CCD, CMOS)

Advantages of greater data cadence
CzeV404 Her (dwarf nova) eclipse (CCD, CMOS)



Advantages of greater data cadence
Flare star: whole night (left), detail (right)





Can the CMOS based C4-16000 replace the best G4-16000 CCD camera?

- The way the GSENSE4040 CMOS sensor is manufactured (4 segments) complicates its usage in astro-photography
- But for **scientific applications**, the CMOS based camera is obviously a **good replacement** of its CCD predecessor
- Testing require data from multiple nights, precision is influenced by weather, phase of the Moon etc.
- Higher quantum efficiency, lower pixel capacity and lower read noise allow better time resolution of photometric series
- Higher sensor temperature is obviously not a significant obstacle
- Greater amount of data increase requirements for processing and storage
- Virtually “zero” download time may bring interesting research capabilities

Thank you for your attention

Questions?

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