How to Choose an Astronomical Imaging Camera

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In 1949, the Hale Telescope on Mount Palomar was opened. At that time, it was the largest in the world—and the most productive. But for decades afterwards, telescopes stopped getting bigger.

The reason? Economics and technology are one answer, but perhaps the real answer is the invention of the CCD camera—which solved many of the problems associated with photographic plates.

Thanks to CCD cameras' superior and rapidly improving sensitivity, astronomers could see much deeper into the cosmos without having to build ever larger telescopes. (Only when CCD cameras approached 100% quantum efficiency—which meant that increasing sensitivity became impossible—was there a major impetus to develop the new technologies required to build larger observatory telescopes.)

Of course, these same advantages apply to smaller telescopes. Over time, the instruments became less expensive, and smaller college and amateur telescopes were fitted with CCD cameras.

Clearly, the choice of camera is key to getting the most bang for your buck in astronomical imaging. The most important factor is not whether it is a CCD or CMOS camera—it's really about matching your camera to the imaging system.

This guide provides an overview of what features to look for in your next astronomical imaging camera.

Resolution—Matching to Your Instrument

The first thing to consider is resolution: how much of the sky does each pixel see?

Smaller pixels will give you higher resolution, but they will also see less sky and collect fewer photons. In that respect, having a larger pixel is much like having a faster focal ratio. But if you make the pixels too large you'll have little square stars—and your resolution will be very poor.

To match your camera's pixel size to your telescope's focal length, use this simple formula:

Pixel Size (arc-seconds) = 206 * pixel size (microns) / focal length (mm)

At premium mountaintop observing sites, atmospheric seeing limits your resolution to around 1 arc-second (usually measured as Full Width Half Maximum, or FWHM). Only the best sites like Mauna Kea can provide sub-arc-second seeing. If you are not on a mountaintop, your typical seeing is likely 2 to 3 arc-seconds.

Let's assume you want good resolution for the best nights, when your seeing disk is 2 arc-seconds FWHM. The Nyquist Sampling Theorem says that for maximum resolution, you need 3 pixels across the FWHM. Therefore, at 2 arc-seconds you need a pixel size that gives you around 0.7 arc-second sampling. You will want to select a camera that gives you 0.5 to 0.9 arc-seconds with your telescope.

The table to the right will save you the trouble of finding a calculator.

Pixel Size, Microns

FL, mm	3	4	5	6	7	8	9	13	15	20	24
500	1.24	1.65	2.06	2.47	2.88	3.30	3.71	5.36	6.18	8.24	9.89
750	0.82	1.10	1.37	1.65	1.92	2.20	2.47	3.57	4.12	5.49	6.59
1000	0.62	0.82	1.03	1.24	1.44	1.65	1.85	2.68	3.09	4.12	4.94
1250	0.49	0.66	0.82	0.99	1.15	1.32	1.48	2.14	2.47	3.30	3.96
1500	0.41	0.55	0.69	0.82	0.96	1.10	1.24	1.79	2.06	2.75	3.30
1750	0.35	0.47	0.59	0.71	0.82	0.94	1.06	1.53	1.77	2.35	2.83
2000	0.31	0.41	0.52	0.62	0.72	0.82	0.93	1.34	1.55	2.06	2.47
2250	0.27	0.37	0.46	0.55	0.64	0.73	0.82	1.19	1.37	1.83	2.20
2500	0.25	0.33	0.41	0.49	0.58	0.66	0.74	1.07	1.24	1.65	1.98
2750	0.22	0.30	0.37	0.45	0.52	0.60	0.67	0.97	1.12	1.50	1.80
3000	0.21	0.27	0.34	0.41	0.48	0.55	0.62	0.89	1.03	1.37	1.65
3250	0.19	0.25	0.32	0.38	0.44	0.51	0.57	0.82	0.95	1.27	1.52
3500	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.77	0.88	1.18	1.41
3750	0.16	0.22	0.27	0.33	0.38	0.44	0.49	0.71	0.82	1.10	1.32
4000	0.15	0.21	0.26	0.31	0.36	0.41	0.46	0.67	0.77	1.03	1.24
4250	0.15	0.19	0.24	0.29	0.34	0.39	0.44	0.63	0.73	0.97	1.16
4500	0.14	0.18	0.23	0.27	0.32	0.37	0.41	0.60	0.69	0.92	1.10
4750	0.13	0.17	0.22	0.26	0.30	0.35	0.39	0.56	0.65	0.87	1.04
5000	0.12	0.16	0.21	0.25	0.29	0.33	0.37	0.54	0.62	0.82	0.99
5250	0.12	0.16	0.20	0.24	0.27	0.31	0.35	0.51	0.59	0.78	0.94
5500	0.11	0.15	0.19	0.22	0.26	0.30	0.34	0.49	0.56	0.75	0.90
5750	0.11	0.14	0.18	0.21	0.25	0.29	0.32	0.47	0.54	0.72	0.86
6000	0.10	0.14	0.17	0.21	0.24	0.27	0.31	0.45	0.52	0.69	0.82
6250	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.43	0.49	0.66	0.79
6500	0.10	0.13	0.16	0.19	0.22	0.25	0.29	0.41	0.48	0.63	0.76
6750	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.40	0.46	0.61	0.73
7000	0.09	0.12	0.15	0.18	0.21	0.24	0.26	0.38	0.44	0.59	0.71

As an example, if you have a telescope with a 3000 mm focal length and seeing around 2 arc-seconds FWHM, then the table shows that you ideally want a pixel size in the 7 to 9 micron range.

Field of View

The second consideration is how much sky you will see.

Going to higher resolution means you will see less sky. In some cases, you might want to sacrifice some resolution to get a wider view. Or, you can buy a camera with a larger sensor—though that will obviously cost more.

Once again, some simple math helps. If each pixel sees 1 arc-second, and you have 1000 pixels across your sensor, you will have 1000 arc-seconds across your chip. Dividing by 60 gives you 16.6 arc-minutes. Divide by 60 again and you have 0.28 degrees. The full moon is about 0.5 degrees across—telescopes do have tunnel vision!

Consider a larger camera with 9 micron pixels in an array of 4096 pixels square (16 megapixels). In the aforementioned example of the 3000 mm focal length telescope, that camera will see a 40 arc-second square on the sky. That's pretty good: high resolution and a good chunk of sky.

If you want to see more sky with a smaller camera, use a shorter focal length telescope. In this case, you can trade off resolution for cost.

Sensitivity vs. Noise

More sensitivity is always better. You can see fainter targets with the same exposure time.

Modern cameras do quite well on this measure. If your sensor has a quantum efficiency (QE) of 50%, that means half the photons of light that hit it are recorded. Most modern sensors are better than 50% QE.

The best sensors approach 100% QE, but at a price: they are more expensive as they use “back-illuminated” technology. The manufacturing technology for producing back-illuminated sensors has been improving, primarily due to demand for better and better cell phone cameras. This technology is now finding its way into the larger scientific and industrial sensors.

Signal is great, but only if there is more signal than noise. In order to reliably detect a star, it needs to have a signal about 3X larger than the noise background. But where does noise come from?

Sources of noise

Let’s assume your image has been properly calibrated, so there is no “fixed pattern noise” and other effects. There are several sources of noise, but it turns out that only the largest one really matters (noise adds root-sum-square):

- The first source of noise is called **read noise.** It’s caused by the electronics in the sensor, which read out the pixels. Noise figures typically range from 1 to 10 electrons. You can’t tell a noise electron from a photoelectron, so the noise could limit how faint you can see. The read noise is produced once every time the sensor is read out, so longer exposures help reduce its importance. If you want to take short exposures, though, read noise becomes important.

- The second source of noise is **dark current noise.** Thermal vibrations in your sensor’s silicon material cause electrons to be produced at random—but at a certain consistent average rate depending on temperature. You can subtract off the dark current with a “dark frame,” which is part of the calibration process, but you can’t get rid of the extra noise in the dark current. Every time the dark current quadruples, the noise doubles. Cooling reduces the dark current rate, and reduces the noise. On very long exposures through narrowband filters, dark current can be the most important noise source.

- The third source of noise is **photon shot noise.** Photons of light are a lot like dark current—if a star has a particular brightness, the photons from it arrive at a constant rate. However, each photon arrives at random. The result is the light itself produces noise. As the number of photons quadruple, the amount of noise doubles. You can see that more light is still better, but nothing is free! If you have a bright sky background, perhaps due to light pollution or moonlight, your noise will be much worse. Even in a dark sky site there is natural sky glow. Narrowband filters greatly reduce the sky background, which is why they are popular.

How noise affects your camera choice

Low read noise is better, but it is not necessarily the most important parameter—unless you know you will be taking very short exposures. Meanwhile, dark current noise can also be important, especially if you plan on taking long exposures with narrowband filters. In that case, a camera with better cooling will be helpful. However, it is important to note that different sensor models have very different dark current characteristics; some have 1000X more dark current than others at the same temperature.

Figuring all this out can be complicated. As a rough rule of thumb, the most important parameter is Quantum Efficiency (QE), followed by how much dark current there is at operating temperature, followed by read noise. If you know you will be taking long exposures, focus on dark current. If you expect to be taking very short exposures, pay more attention to read noise.

Guiding

The world's most sensitive camera on the largest telescope you can get certainly sounds great—but the images will be terrible if the mount is unable to track the stars accurately enough. The stars will all be trailed across the image. While some very expensive mounts can now do this nearly perfectly, the mount still needs to be very accurately polar aligned. And even then there is atmospheric refraction, wind vibration, and more to contend with.

The usual solution to these problems is autoguiding.

When you are guiding, an auxiliary camera locks on to a moderately bright star, and constantly images it and measures its position via software. When the star drifts slightly off target, commands are sent to the mount to recenter it. Since software can measure the star to a tiny fraction of a pixel (1/10th to 1/20th of a pixel), the autoguiders do not need extremely high resolution. For this reason, sometimes a separate guide telescope is used; however, this only works if the main telescope and guide scope mounting is perfectly rigid. A small motion on the order of microns is all it takes to cause trailed images. "Mirror flop" is a common hazard, especially in Schmidt-Cassegrain style telescopes.

A more sophisticated and faster-reacting technique is to use adaptive optics accessories, which work in conjunction with autoguiders to provide very rapid and precise correction of any drift. Adaptive optics are also fast enough to improve on slow seeing effects.

Software

While the camera itself is very important to what imaging performance you get, your observing experience and the productivity of your imaging session largely depends on software.

Your camera will ideally come with tools needed to:

- ✓ Locate your target
- ✓ Focus accurately
- ✓ Autoguide
- ✓ Take sequences of exposures using different filters

For even more capability, consider upgrading to a camera that provides complete observatory integration and a wider variety of advanced imaging tools.

Conclusion

Of course, cost is also an important factor in your decision-making—with larger cameras costing more than smaller ones.

That said, quality and service should also play a critical role in your choice. It is certainly possible to purchase very inexpensive cameras made overseas with low quality and little—if any—customer support. But is that good value if you cannot get the results you want, or if you have to replace it after just six months?

For this reason, look for a camera with at least a two-year warranty, a warranty of one year for the sensor itself—and seek out a manufacturer that is well-known to provide high quality, reliable, friendly and always-helpful customer support.