Uncool Imaging Video Cameras and Uncooled Imagers

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In the last few years, development of a robust consumer market for solid state imaging has led to the creation of several new products that can now be used for astronomical images. These devices are now produced in sufficient quantity that they are priced within the means of most interested amateurs. Normal prices of consumer grade imagers are about 1/10th the price of similar format cooled scientific imagers. Examples of such new uncooled imagers include

Fig. 1. Meade LPI Uncooled Camera

Fig. 2: Adirondacs Integrating Video

Fig. 3. Digital Still Cameras

Fig. 4. Modified Web Cameras

Using an uncooled consumer imager for astronomical imaging is very similar to using a scientific camera in many ways, but uncooled imagers have some characteristics that require different techniques to reach their full potential. This article seeks to explain how to use these uncooled imagers to their best effect and to recognize and characterize their fundamental limitations.

Contrasting The Technologies
Consumer grade imagers actually offer some advantages relative to cooled scientific imagers. Foremost among these is price. An uncooled VGA format imager can be purchased for around $100 USD, while the least expensive cooled CCD of similar dimension costs about $1500. Similarly, large format digital still cameras in the 4 mega-pixel range cost about $1000 USD, while cooled CCD cameras in the same format run upwards of $10,000 USD.

Like cooled CCD's, consumer grade imagers offer the advantages of direct digital readout and linear response to light over their useful dynamic range. Thus, both are arguably superior to film in this respect. Consumer grade imagers however, tend to have fewer bits per pixel than scientific imagers. Typical uncooled sensors have 8 to 10 bits of resolution, while cooled CCD's tend to have 12 to 16 bits per pixel. Newer families of consumer grade imagers are now starting to appear with 12 to 16 bit resolutions.

Due to the efforts of several dedicated amateurs and some professionals, there is a wide variety of software that is either bundled with the cameras, or inexpensively available off the Internet for science data acquisition with these cameras. Once image acquisition is complete, the same image reduction and processing packages that are commonly used with cooled cameras can be used. Some such common packages include IRAF, CCD-OPS, Maxim DL, Autostar IP, and Astromet,.

Although a few uncooled imagers are available with monochromatic sensors, most common models are "one shot" color imagers. In this respect they differ from cooled scientific cameras. This is both a benefit and detriment. One does obtain a perfectly registered and color balanced image in a given exposure, but in doing so, one sacrifices spatial resolution. The figure below is illustrative of the problem:

R	G	R	G	R
G	B	G	B	G
R	G	R	G	R
G	B	G	B	G

Fig. 5. Bayer Pattern Overlay

The imager is overlayed with a set of filters deposited directly on the surface of the imager. Typically, these filters are in the form of a Bayer Pattern where a 2x2 submatrix of the pixels has the form:

$$\begin{bmatrix} G & R \\ B & G \end{bmatrix}$$

This pattern has two undesirable effects, first it means that you need to over sample by a factor of 2X relative to a monochromatic sensor to assure the same astrometric accuracy. Secondly, by doubling your sample rate, you get ¼ the light falling on a given pixel, requiring longer exposure of your image to achieve comparable signal to noise ratios. Finally, the filter material deposited on these chips is not as transmissive as the interference filters used with cooled scientific imagers. Epitaxially deposited filters are typically only half as transmissive as interference filters.

The defining difference in consumer cameras is the lack of active cooling of the imagers. The lack of active cooling means that the thermal noise in these imagers is higher. While thermal noise can be effectively reduced by dark subtraction techniques, it is the buildup of thermally generated electrons in these sensors that ultimately limits the duration of the exposures that can be obtained. When the accumulation of thermally generated electrons added to the imaged photo-electrons exceeds the linear operating range of the sensor, you have reached the maximum exposures. The good news is that fabrication processes and packaging have improved to the point where some of these sensors can be run up to several minutes before this practical limit is reached. In practice, exposure times of 15 to 60 seconds are more typical.

One of the positive impacts of the relatively short exposure times is that for most applications, no telescope guiding is required. Most good, properly aligned mounts track well enough open loop to allow 20 second exposures without objectionable trailing. Since images will be built up by combining multiple exposures, guiding can be eliminated in favor of shifting and aligning the individual images prior to combining them. Another benefit of this combination of many frames is that variation in the seeing and tracking, tend to naturally cause the images to be dithered enough to compensate for the Bayer pattern filters. In other words, you do not suffer the loss in astrometric accuracy if a statistically large number images are combined.

Advanced software uses a stacking method known as "Drizzle" that can actually improve the quality of the image by up to a factor of two. This is the technique used by the Space Telescope Science Institute to improve the resolution of the Hubble Deep Field images.

The Mathematics of Stacking

To compensate for the limited exposure time of an uncooled imager you must, instead of taking a single long exposure, take a series of shorter exposures and add, average or otherwise combine them together to build up a good image. This stacking of many, many images is the key to getting good results with uncooled cameras.

In order to understand how good an image we can get relative to a comparable cooled imager, we need to talk about image quality in terms of signal to noise ratio, or S/N. This is an unbiased quantitative measure of image quality. It is the ratio of signal information to the random contamination in an image. Perceptually, images with poor signal to noise ratios appear "grainy".

For the sake of this discussion, let us assume that we have two imagers. One is cooled and one is not. Further, assume that the sole source of noise in our images is read noise, and both cameras' read circuits perform equivalently. Read noise results from random effects while digitizing the pixels and reading them out of the camera. While this is not strictly the case in the real world, it is the most significant component of noise after we have performed our dark subtraction. Suppose that for a cooled camera we have the following system read noise

$$S/N(exposure(T)) \ = \ X$$

Increasing the exposure time by a factor of m will therefore improve the signal to noise ratio to:

$$S/N(exposure(mT)) = mX$$

Simply because we have gathered ***m*** times as much signal and still have only one read's worth of noise in the image. For our uncooled imager, if our maximum exposure time is ***T***, then we must take ***m*** exposures and add them together. Doing so does not achieve the same signal to noise ratio. Due to the net effects of averaging noise, our signal to noise ratio is:

$$S/N(m \times exposure(T)) \cong \sqrt{m}\,X$$

This demonstrates the fundematal limitation of image stacking. For equal total exposure times, uncooled imagers signal to noise ratio under performs a single long exposure by the one over the square root of the exposure count.

To understand what this means in practical terms let us work through an example. Assume:

1. Our uncooled imager can take exposures up to 10 seconds before running out of dynamic range.
2. It has filters ½ as transmissive as the interference filters on the monochromatic cooled camera.
3. The read noise performance of the cameras is similar.
4. The cooled camera will needs to take 3 exposures, R, G and B filtered.

The question we need to answer is: "How many exposures and how much time will it take to make a color image with our uncooled camera as good as one made from 3 one minute filtered imagers with the cooled camera?" For the cooled camera we get the signal to noise by applying the functions above.

$$S/N_{cooled}(exposure(60)) \cong X$$

With our uncooled camera our S/N in a single image is as:

$$S/N_{uncooled}(exposure(10)) \cong \frac{X}{12}$$

Since we need 12 squared images to get to the same signal to noise ratio, we get the following total times:

$$Time_{cooled} = 3 \times 60 = 180sec = 3min$$

$$Time_{uncooled} = 12^2 \times 10 = 1440sec = 24min$$

This example clearly demonstrates both the benefits and limitations of using uncooled imagers. Firstly, the analysis ignores the difficulties and time involved with framing and focusing the target. Assuming you are a skilled technician, this effort can still take a couple of minutes. Even so, it is pretty clear that the user of a cooled camera is going to be more productive than you are. The consolation is you spent a whole lot less money, and as an amateur, you are supposed to be enjoying the time you spend doing this, so you get more fun per image!?

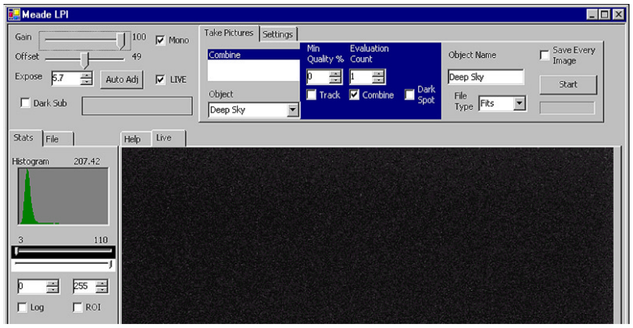
Tips and Tactics

There are several other key elements that go into making successful images with uncooled imagers. Firstly, select the best imager possible. There are two technologies prevalent in the market, CMOS and CCD. CMOS imagers are cheaper since both the imager and readout electronics can be placed on a single chip. CMOS's drawback is that it has significantly lower QE than CCD chips. If possible select a camera with a CCD image sensor.

Regardless of what sensor you have, you must be able to **Turn Off All Compression**. Image compression for all of these consumer grade imagers is lossy. That means information is lost during the compression process. Data compression will make it impossible to dark subtract, calibrate and benefit in any predictable way from stacking. Be sure the camera you select allows you to save images without compression.

Similarly, the camera must allow you to override any automatic gain control, and black or white level settings. At a minimum, you must be able to disable AGC. If the gain changes from image to image, you cannot sensibly combine or calibrate them. Some cameras automatically set the black level. This can make it difficult to perform dark subtraction. There are some software packages with routines that attempt a dynamic, least noise offsetting of dark frames for cameras that cannot disable automatic black level controls, but it is much easier if this problem can be avoided.

Set the black offset control below the background level so that no pixel in your dark frames has a zero values. This guarantees you will be able to calibrate all your images effectively. The histogram in Figure 6 demonstrates how properly configured image capture software should appear.



Gain 100
Offset 49
Expose 5.7
☑ Mono
☑ LIVE
☐ Dark Sub
Combine
Object: Deep Sky
Min Quality %: 0
Evaluation Count: 1
☐ Track
☑ Combine
☐ Dark Spot
Object Name: Deep Sky
☐ Save Every Image
File Type: Fits
Histogram 207.42
0
255
☐ Log
☐ ROI

Fig. 6. Meade LPI Acquisition Software

Further on the subject of dark frames, though the camera may not be cooled, that does not mean that it runs at a constant temperature. The electronics in the camera generate heat. This generated heat needs to be dissipated to the outside environment. Only when the camera sheds heat at the same rate that it generated it does it reach thermal equilibrium with its environment. Only then will its temperature stabilize. You should therefore, start your camera running at the frame rate and exposure time you will be using and give it some time to reach equilibrium, then take your sequence of dark frames. As with everything we do with uncooled imagers, you should take many (50+) dark images and average them together to form your master dark image. Additionally, you need to take new darks anytime the point of thermal equilibrium changes. That can mean an increase in the breeze that changes convective cooling, or a drop in the ambient temperature as the night deepens. Additionally, you will need to take new darks whenever you change the camera duty cycle, exposure time or inter frame delay.

If possible, you should get an imager that has square pixels. Imagers without square pixels are going make astrometry and photometry more difficult. You will have to resample your images. In doing so, you will need to use a routine that is flux conserving. This means that the scaling routine must accurately preserve the total ADU counts in your images even after scaling. There are not many Windows based image processing programs that satisfy this requirement.

Always expose at the highest ISO or gain setting available with your camera. Most uncooled imagers have a limited number of bits per pixel, that means that they are coarsely dividing the signal you are receiving. Since our exposures are necessarily short anyway, better to turn up the gain and spread these over as large a range as possible.

Use floating point pixels when combining your images. Related to the previous comment, you are attempting to make up in quantity, what our imager lacks in quality. It is important the software you use to combine images keeps track of the fractions of pixel values. One way to appreciate this is to suppose you add 8000 eight bit images together. If your program cannot represent numbers larger than 65536 (16 bits) you will end up with numerically saturated images since the largest value you might reasonably obtain is 2,040,000. Furthermore, you probably do not want to add your images, but rather average them. This will allow you to reasonably compare runs from different nights made up of different integration periods. Under these conditions, floating point numbers are a requirement.

Another implication of the tactic of stacking overwhelmingly large number of images is that you either need software that can do this on the fly, or you are going to need lots and lots of memory. Particularly if you are a digital still camera user, bring lots of chips, or a pair of them and a computer so that you can read one into the computer while you fill the other.

The Video Fallacy

The notion that you will ever be able to achieve satisfactory results with web cameras or video cameras that have maximum exposure times of a fraction of second is fallacious. You are going to have to get a digital still camera, modify a web camera for long exposures, or purchase one of the new uncooled astro imagers that allows longer exposures. To illustrate this point let us revisit the stacking example above, except assume you have a video camera that can only expose 1/60th of a second images. Again assume you have the same read noise as the cooled imager and filters with 50 percent the transmissivity. Again we have the S/N for the cooled camera:

$$S/N_{cooled}(exposure(60)) \cong X$$

For our video web camera we have:

$$S/N_{uncooled}(exposure(\tfrac{1}{60})) \cong \frac{X}{7200}$$

Now look at the time comparison:

$$Time_{cooled} = 3 \times 60 = 180sec$$

$$Time_{uncooled} = 7200^2 \times \frac{1}{60} = 2864000sec = 240hrs!$$

The conclusion is obvious. Save video for targets that are very bright such as planets and the Moon. For planetary images, the short exposure time which hinders your efforts at deep sky photography actually benefits you by allowing you to employ selective image reconstruction. An uncooled imager can even outperform cooled imagers in this regime. The method takes many images and selects only those images that freeze instants of perfect seeing and combines and aligns only those images. In order to make very short exposures, most uncooled imagers are electronically shuttered, so they transmit no mechanical vibration to the telescope as shutters open and close. Additionally, the support streaming output formats that are better suited to storing and processing collections of upwards of 50,000 images.

Image Acquisition Software

The key to using an uncooled camera is to gather many images under controlled circumstances and combine them. Doing such a thing manually is beyond tedious. With uncooled imagers you are not talking about tens of images, you are talking about hundreds, thousands and tens of thousands of images. Processing such collections by hand, or using point and click image processing is unthinkable. To solve this problem several good software packages are available. Though they differ slightly in philosophy and emphasis, they all do a reasonably good job of automating this process. While I am sure I am omitting some worthy entries, here is a partial list of what is available and some key elements of the package.

Astro-Snap

http://www.astrosnap.com/index_uk.html

Complete acquisition system for modified web cams, scope control, camera assisted alignment, and limited off line processing.

AstroVideo

http://www.ip.pt/coaa/astrovideo.htm

Complete acquisition system for video or modified web cams, scope control, alignment, selection, autoguiding, ftp support.

Autostar Suite

http://www.meade.com

Bundled with Meade LPI. Automated, on the fly dark calibration, alignment and stacking. Automatic image selection. Autoguiding. Full featured offline image processing.

AviEdit

http://www.am-soft.ru

Avi stream capture, assembly, disassembly and editing. Useful for converting AVI streams to collections of BMP images for offline processing.

K3 CCDTools

http://www.pk3.org/Astro

AVI stream capture, assembly, disassembly, good time lapse support, FITs output, Alignment, and Image selection.

K3 Nikon

http://www.pk3.org/Astro

Palmtop control of the Nikon Cool pix cameras. Programmable cable release.

Suitable and Unsuitable Projects

Now that I have gone over the mechanics of acquiring and operating an uncooled imager, I want to consider what are reasonable and unreasonable uses for such devices.

Pretty Pictures:

Clearly, the first thing you want to do is take some pretty pictures. Firstly, it develops your skill and technique with the new system. It also helps you justify the time and expense to your significant other. In this category, the latest generation of digital still cameras are looking more and more likely to start pushing emulsion based imaging into smaller and smaller niches.

The image in Figure 7 was produced using a Cannon EOS 10D camera. It was made through an Astrophysics refractor combining images totaling about 100 minutes exposure time. Figure 9 images were made with Meade's LPI imager. Figures 10-13 were made with Meade's, soon to be released, Deep Space Imager (DSI).

Occultation:

Beyond pretty pictures, video and webcams are well suited to occultation timing. The better capture programs offer programmable frame rates and exposure times. Images are time stamped by the processor. Provided the computer's clock is synchronized with a GPS, internet time server or other accurate standard, the digital nature of the imager data stream makes handling and processing occultation data much easier. Calibrating video tapes will become a thing of the past. Additionally, electronically shuttered cameras can look deeper than video. Integrating for a second per image allows you to look up to 4.5 magnitudes deeper than video. This alone should increase the number of potentially observable events tremendously. I expect webcams will dominate occultation timing in the near future. Figure 8 shows two frames from a sequence taken of Callisto being partially eclipsed by Ganymede.

Fig. 7: Andromeda Galaxy

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Planetary Studies

Without question, webcams and selective image reconstruction techniques have changed the way we observe planets. Reviewing the world wide web and popular literature over the past year, I routinely see planetary images that a few years ago I would have concluded came from spacecraft or our most accomplished imagers. The ease of imaging the planets with uncooled imagers provides amateurs with opportunities to push the frontiers of planetary observing. Among potential long term projects are monitoring the Moon for transient lunar phenomena, weather studies of Mars, cloud and vortices tracking on Jupiter and Saturn.

Fig. 8a. Ganymede and Callisto out or eclipse

Fig 8b. Ganymede partially eclipsing Callisto

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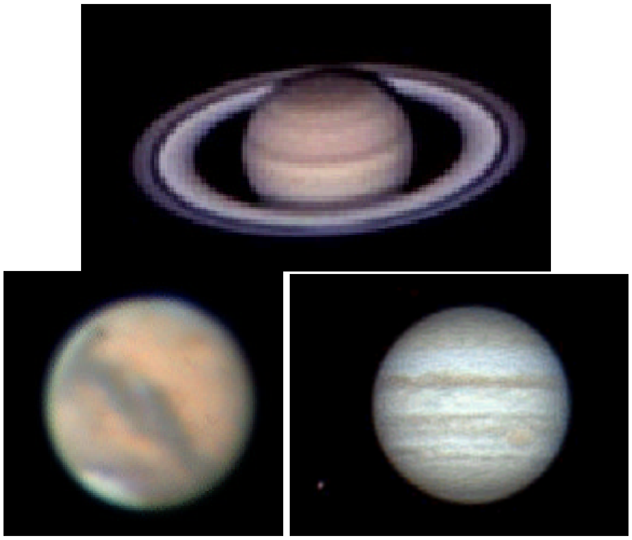

Fig. 9 Typical webcam planetary images.

Figure 10: M27 with Meade's New DSI (10 min)

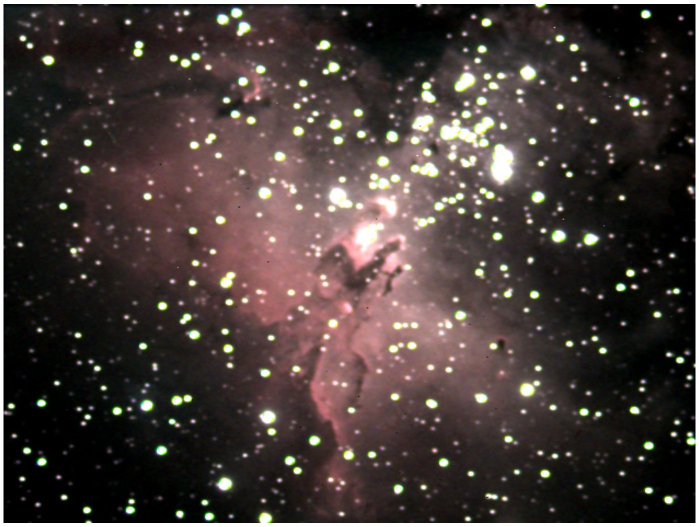

Figure 11: M16 with DSI (8 min.)

Multiple Star Astrometry

Although modern surveys vacuum the skies for transients, spectra, and asteroids, relatively few observers are deeply involved in positional astronomy, once a mainstay of the science. Uncooled imagers offer amateurs a unique opportunity to study bright close binary star systems astrometrically. Multiple star systems in the brightness range, magnitude 1 to 6 are too bright for most large professional telescopes. Although Hipparcos and Tycho measured these objects, the relatively short duration of that mission does not allow the catalog to absolutely separate high proper motion stars from longer period multiple systems. Using selective image reconstruction techniques, combined with data mining of Tycho/Hipparcos data and available plate libraries such as DSS, there are opportunities for amateurs to help refine orbital elements of multiple star system astrometrically.

Figure 11: DSI Image of M100 (10 min)

Long Period Variable Star Photometry

Long period variable star studies have long been one of the mainstays of amateur astronomical science. The inexpensive availability of uncooled imagers should hasten the end to visual magnitude estimation. With moderate care, differential photometric observations accurate to +/- 0.05 magnitudes are within the reach of almost any observer.

Unsuitable Activities

Due to the longer integration times required by uncooled imagers, some project, such as asteroid discovery, should be skipped. This work now has mostly been assumed by the surveys. Additionally, these detectors are not well suited to spectroscopy or other imaging where photons are limited.

Figure 13: M51 with DSI (10 min.)

Conclusions

We are involved in amateur astronomy at the cusp of the next technological breakthrough. High quality imaging cameras are about to drop in price by a factor of nearly 10. The next generation of digital astronomy cameras are going to have retail prices below $250. The development of inexpensive uncooled imagers that can be adapted to the service of astronomy has created an opportunity to bring quantitative observation within the means of many more amateur astronomers.

Amateurs who have long histories in digital imaging are the ones who have the experience and knowledge to foster development of this emergent technique. While it may be a retrograde step in their observing, they can make a contribution by promoting and assisting amateurs who elect to use this means to venture into quantitative observation for the first time.

I expect that imager development will follow a price/performance trend similar to Moore’s law for semiconductor development. With the prices halving every few years, or the pixels quadrupling for the same dollars. If I am correct, the future will see uncooled imaging move progressively into areas formally occupied solely by custom cooled scientific cameras. We are seeing the first step with 10 mega pixel digital SLR cameras below $1000, and digital astro imaging cameras below $125. Without the burden of cooling systems, the next generation of imagers will be smaller, lighter, consume less power and cost significantly less.