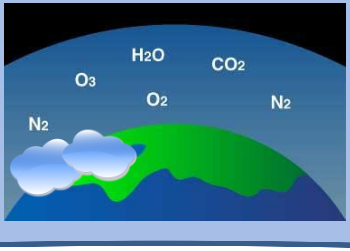
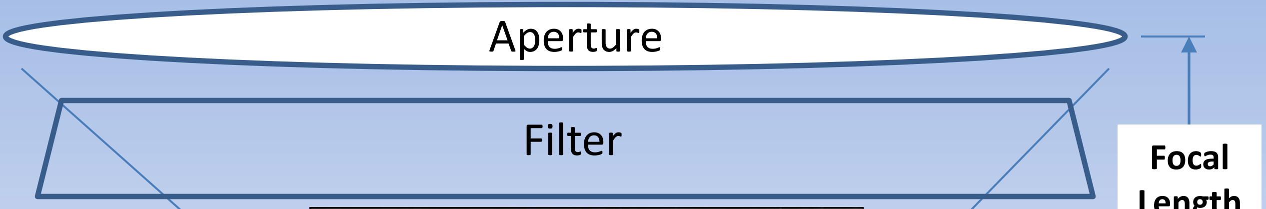
Anatomy of Image Capture





Aperture

Filter

Focal Length

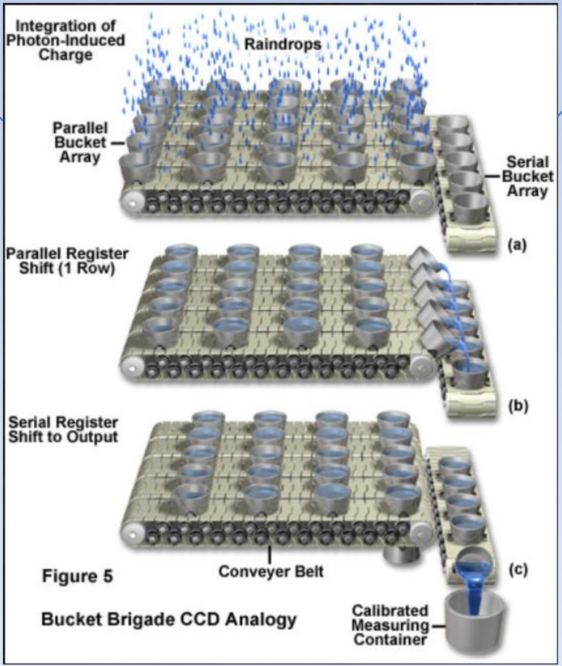


Figure 5

Bucket Brigade CCD Analogy

http://www.microscopyu.com/articles/digitalimaging/ccdintro.html

Thermal Noise

→ **Image Calibration**

- Light from Galaxy and background enters the aperture
- Stray Light entering aperture (Light Pollution)
- How big is the aperture? (more photons, more stray light)
- Shorter focal length sees more sky and collects more rain (photons). (Brightness)
- Anything partly blocking some buckets (Optical aberration, vignetting)
- Glass blocking certain colors from reaching buckets (Filter)
- How big are the buckets (pixel size)
- With even rain, think each bucket will get the exact same amount? (Shot noise)
- Will each bucket detect each rain drop? (Quantum efficiency)
- Each time you read from the calibrated container, think you'll read exactly the same each time? (Read noise)
- When dumping, does every bucket dump 100% of the water? (Bias)
- Heat causes detector to measure additional rain in bucket (Dark Current)
- Each time you read from the heated calibrated container, think you'll read exactly the same each time (Dark noise)

Idea taken from http://www.stark-labs.com

Objectives

The intend of this presentation is to provide

1) The necessary background and definitions to understand what is involved in image capture

2) The constraints that bound the selection of an image capture strategy

3) The sensitivity analysis that provides the insight to choose an image capture strategy that meets your definition of a great image

4) Example of possible image capture options

5) Demonstrate the benefits and regrets of each image capture option

Agenda

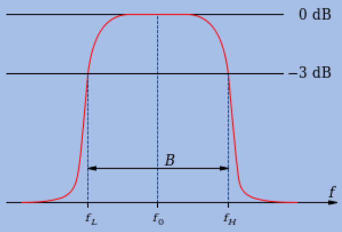
- Astro-Photography Definitions with some examples
- Capturing Faint Detail with Astrophotography
  - Signal-to-Noise (SNR) Intro
  - Methods of Improving SNR
    - Calibration and Stacking
    - The Darker the Skies, the better the Image
  - Defining SNR with and without Stacking
  - Estimating Exposure Times and Number of Subs
  - Image Capture Strategies
    - SNR
    - Resolution
- Summary
- Conclusions

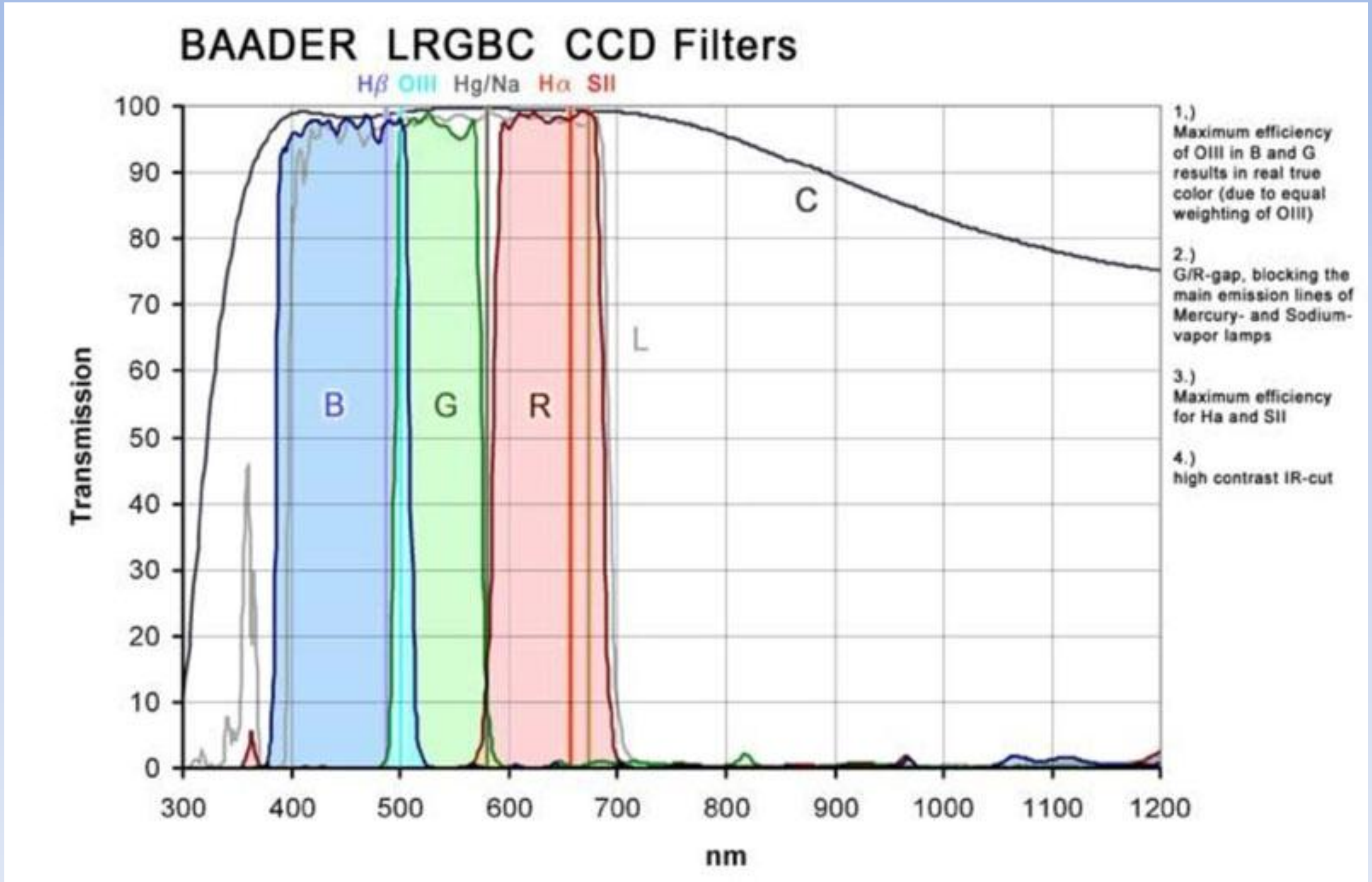
Definitions

- **Aperture** (in) - Diameter of telescope optics
- **Focal Length** (mm) – Distance between cameral focal plane and aperture
- **Focal Ratio** - Focal length (mm) divided by aperture diameter (mm)
- **Camera Field-of-View** (deg) – 57.296*Camera Chip dimensions (mm) divided by focal Length (mm)
- **Pixel size** (microns) – Dimension of a camera pixel
- **Image Scale** (arc-sec/pixel) – 206.265*Camera pixel dimension (microns) divided by focal length (mm) (Note: 206265. constant is radians to arc-sec conversion)
- **Pixel Binning** – According to Wikipedia (https://en.wikipedia.org/wiki/Data_binning) , "…binning is the procedure of combining a cluster of pixels into a single pixel. As such, in 2x2 binning, an array of 4 pixels becomes a single larger pixel…." Binning is used to increase signal at the cost of a lower resolution.
- **Resolution** - Resolution is a major factor in determining fine detail SNR such as that of stars. Increased resolution gives increased SNR. However, sampling is an important factor as well. Undersampled images (such as those taken with short focal length scopes and/or binned CCD chips) will have worse SNR than properly sampled images. http://starizona.com/acb/ccd/advtheoryexp.aspx

Definitions – Filter bandwidth

- **Filter bandwidth** – According to Wikipedia, “Passband bandwidth is the difference between the upper and lower cutoff frequencies of, for example, a band-pass filter, ……or a signal spectrum. In the case of a low-pass filter or baseband signal, the bandwidth is equal to its upper cutoff frequency.”




BAADER LRGBC CCD Filters

1.) Maximum efficiency of OIII in B and G results in real true color (due to equal weighting of OIII)

2.) G/R-gap, blocking the main emission lines of Mercury- and Sodium-vapor lamps

3.) Maximum efficiency for Ha and SII

4.) high contrast IR-cut

Each R, G, &B Filter reduce photons by ~30% compared to Luminance

Bandwidth
L - ~ 280nm
R - ~ 105nm
G - ~ 85nm
B - ~ 125nm

https://www.baader-planetarium.com/en/blog/the-baader-l-rgb-c-ccd-filters/

Definitions – Filter bandwidth (continued)

L,R,G,B Transmission Comparison

L,R,G,B Transmission curves shown on previous page were Integrated Note: the left hand small spike in Luminance (L) and red filter not included.

	Hand Integrated	Graph Grabber [1]
Luminance	288.16	291.56
Red	----	101.95
Green	----	78.26
Blue	120.79	120.77
RGB Sum	----	300.98

Results

RGB to L ratio	----	1.032

[1] https://www.quintessa.org/software/downloads-and-demos/graph-grabber-2.0

Definitions - Optical Aberrations

- An **optical aberration** is a distortion in the image formed by an optical system compared to the original. They can arise for a number of reasons…due with the limitations of optical components such as lenses and mirrors.
  - **Astigmatism** occurs in lenses because a lens has different focal lengths for rays of different orientations, resulting in a distortion of the image. In particular, rays of light from horizontal and vertical lines in a plane on the object are not focused to the same plane on the edges of the image.
  - **Chromatic aberration** occurs in lenses because lenses bring different colors of light to a focus at different points.
  - **Coma** occurs because off-axis rays not quite converge at the focal plane. Coma is positive when off-axis rays focus furthest from the axis, and negative when they are closest.
  - **Distortion** is caused because the transverse magnification may be a function of the off-axis image distance. Distortion is classified as positive (so-called pincushion distortion), or negative (so-called barrel distortion).
  - **Field curvature** (a.k.a. Petzval field curvature) results because the focal plane is actually not planar, but spherical.
  - **Spherical aberration** occurs in a spherical lens or mirror because these do not focus parallel rays to a point, but instead along a line. Therefore, off-axis rays are brought to a focus closer to the lens or mirror than are on-axis rays.

http://scienceworld.wolfram.com/physics/OpticalAberrations.html

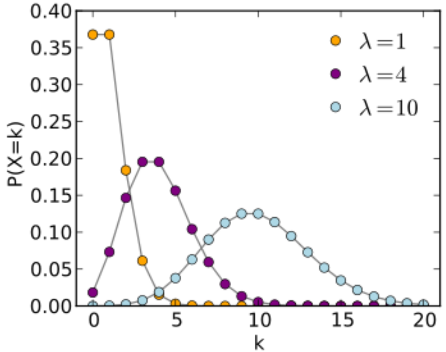
Definitions - Shot Noise

- **Shot noise** or **Poisson noise** is a type of electronic noise which can be modeled by a Poisson process. In electronics shot noise originates from the discrete nature of electric charge. Shot noise also occurs in photon counting in optical devices, where shot noise is associated with the particle nature of light.
- It is known that in a statistical experiment such as tossing a fair coin and counting the occurrences of heads and tails, the numbers of heads and tails after a great many throws will differ by only a tiny percentage, while after only a few throws outcomes with a significant excess of heads over tails or vice versa are common; if an experiment with a few throws is repeated over and over, the outcomes will fluctuate a lot. (It can be proven that the relative fluctuations reduce as the reciprocal square root of the number of throws, a result valid for all statistical fluctuations, including shot noise.)
- Shot noise exists because phenomena such as light…consist of the movement of discrete (also called "quantized") 'packets'. Consider light—a stream of discrete photons—coming out of a laser pointer and hitting a wall to create a visible spot. The fundamental physical processes that govern light emission are such that these photons are emitted from the laser at random times; but the many billions of photons needed to create a spot are so many that the brightness, the number of photons per unit time, varies only infinitesimally with time. However, if the laser brightness is reduced until only a handful of photons hit the wall every second, the relative fluctuations in number of photons, i.e., brightness, will be significant, just as when tossing a coin a few times. These fluctuations are shot noise.

https://en.wikipedia.org/wiki/Shot_noise

Definitions - Shot Noise

- The number of photons that are collected by a given detector varies, and follows a Poisson distribution, depicted here for averages of 1, 4, and 10.



- For large numbers, the Poisson distribution approaches a normal distribution about its mean, and the elementary events (photons, electrons, etc.) are no longer individually observed, typically making shot noise in actual observations indistinguishable from true Gaussian noise. Since the standard deviation of shot noise is equal to the square root of the average number of events *N*, the signal-to-noise ratio (SNR) is given by:

$$\mathrm{SNR} = \frac{N}{\sqrt{N}} = \sqrt{N}.$$

- Thus when *N* is very large, the signal-to-noise ratio is very large as well, and any *relative* fluctuations in *N* due to other sources are more likely to dominate over shot noise. However when the other noise source is at a fixed level, such as thermal noise, or grows slower than sqrt(N), increasing *N* (the DC current or light level, etc.) can lead to dominance of shot noise.

https://en.wikipedia.org/wiki/Shot_noise

Definitions - Poisson Distribution

From Wikipedia, the free encyclopedia

The **Poisson distribution** is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event.

For instance, an individual keeping track of the amount of mail they receive each day may notice that they receive an average number of 4 letters per day. If receiving any particular piece of mail doesn't affect the arrival times of future pieces of mail, i.e., if pieces of mail from a wide range of sources arrive independently of one another, then a reasonable assumption is that the number of pieces of mail received per day obeys a Poisson distribution.

Assumptions: When is the Poisson distribution an appropriate model?

- K is the number of times an event occurs in an interval and K can take values 0, 1, 2, …
- The occurrence of one event does not affect the probability that a second event will occur.
- The rate at which events occur is constant. The rate cannot be higher in some intervals and lower in other intervals.
- Two events cannot occur at exactly the same instant.
- The probability of an event in a small interval is proportional to the length of the interval.
- If these conditions are true, then K is a Poisson random variable, and the distribution of K is a Poisson distribution.

Suppose that astronomers estimate that large meteors (above a certain size) hit the earth on average once every 100 years (λ = 1 event per 100 years), and that the number of meteor hits follows a Poisson distribution. What is the probability of k = 0 meteor hits in the next 100 years?
Under these assumptions, the probability that no large meteors hit the earth in the next 100 years is p = 0.37. The remaining 1 – 0.37 = 0.63 is the probability of 1, 2, 3, or more large meteor hits in the next 100 years.

$$P(k \text{ events in interval}) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Definitions

- **Dark frame** – according to Wikipedia, "A **dark frame** is an image captured with the sensor in the dark, ... A dark frame, or an average of several dark frames, can then be subtracted from subsequent images to correct for fixed-pattern noise such as that caused by dark current. …Visible fixed-pattern noise is often caused by hot pixels – pixel sensors with higher than normal dark current. On long exposure, they can appear as bright pixels.
    - Photosites on the sensor that always appear as brighter pixels are called *stuck pixels* while sensors that only brighten up after long exposure are called *hot pixels*

- **Bias** – according to Wikipedia, "…a **bias frame** is an image obtained from an opto-electronic image sensor, with no actual exposure time. The image so obtained only contains unwanted signal due to the electronics that elaborate the sensor data, and not unwanted signal from charge accumulation (e.g. from dark current) within the sensor itself.
    - A bias frame is complementary to a dark frame, which has a charge integration time but in darkness. Since a dark frame contains unwanted signal including a fixed-pattern noise component, some of which corresponds to the bias frame, and some of which is due to dark current and is proportional to the exposure time, it is possible to obtain an image representing only the dark-current component by subtracting a bias frame from a dark frame.

Definitions

- **Dark Current** - Unwanted current or signal in a photodetector in the absence of incident light, resulting from thermally excited electrons or leakage of current along the current path. http://www.yourdictionary.com/dark-current

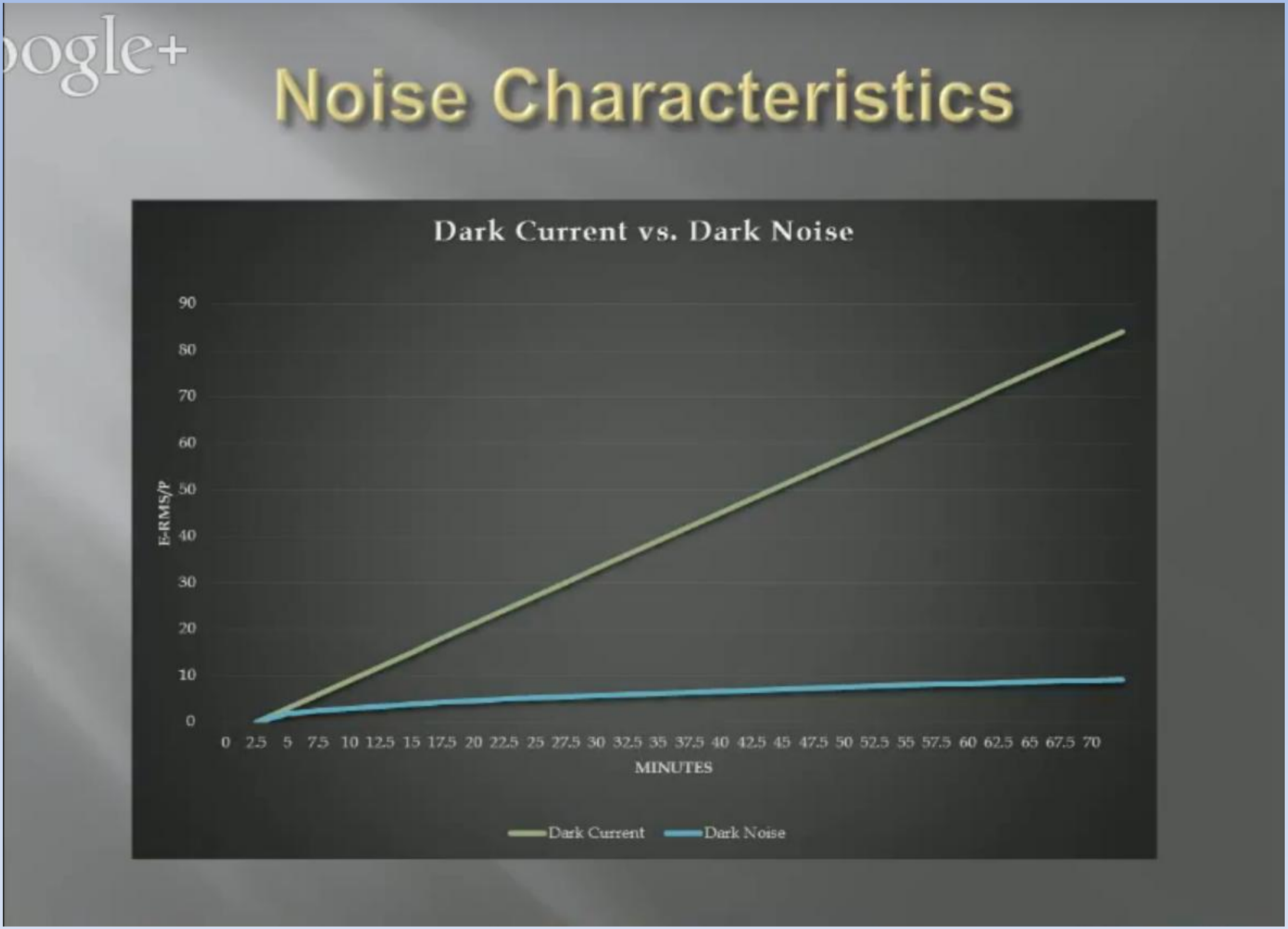
- **Dark noise** - Dark noise is (a) statistical variation in the number of electrons thermally generated within the pixel in a photon-independent fashion, and is the electron equivalent of photon shot noise. Dark noise is calculated from the dark current:

  - Dark current, and therefore dark noise, are temperature dependent, with less noise at lower temperatures. For most biological experiments, dark current and dark noise are negligible over a typical exposure interval of less than five minutes.

$$\text{Dark noise} = \sqrt{(\text{dark current})\ (\text{integration time})}$$

  - Because dark noise is typically negligible for short exposures, the main noise component coming from the camera that may need to be considered is read noise.

http://www.hamamatsu.com/us/en/community/life_science_camera/references/technical_guides/dark_noise/index.html

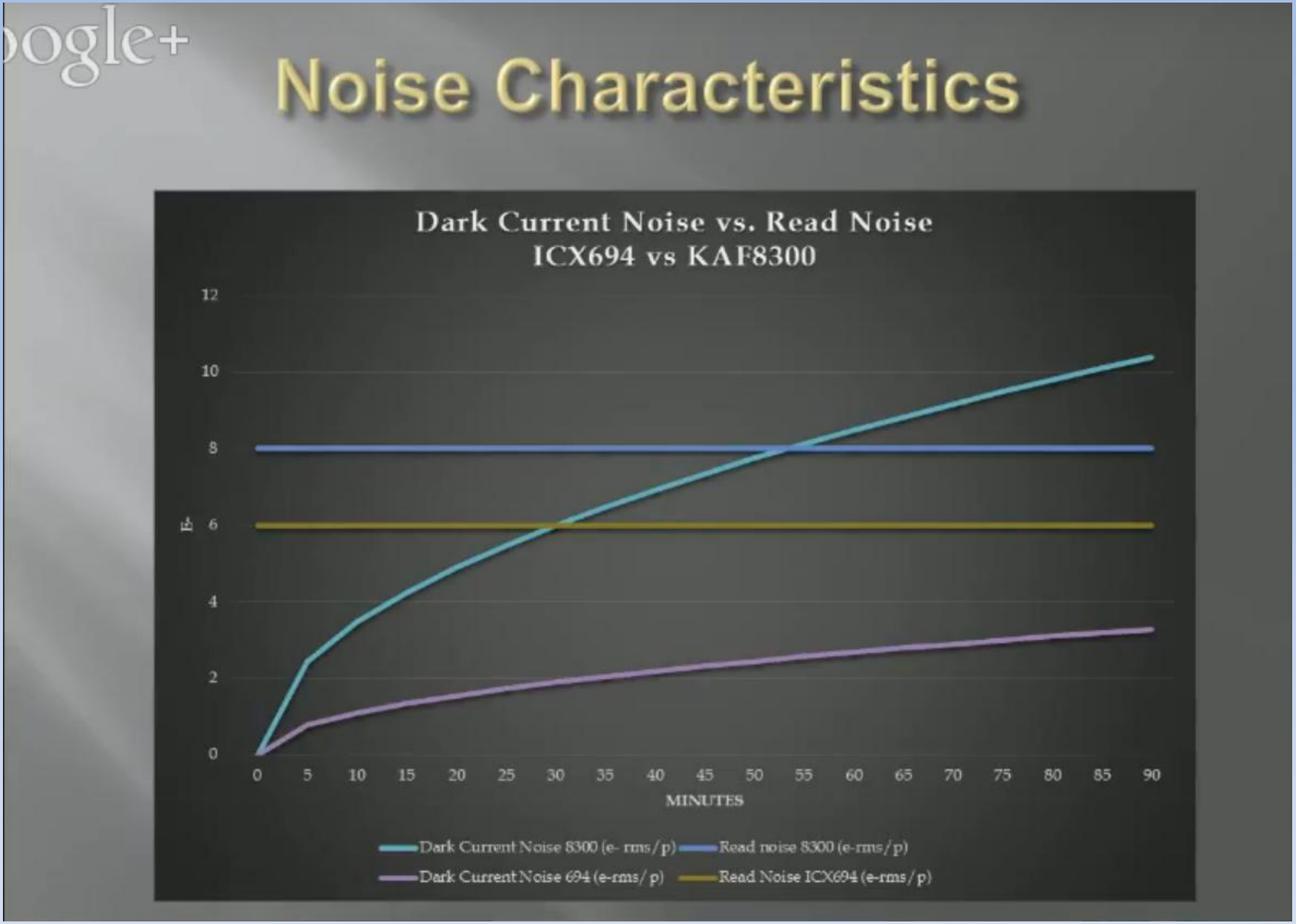


Noise Characteristics

Dark Current vs. Dark Noise

Sensor: KAF-8300

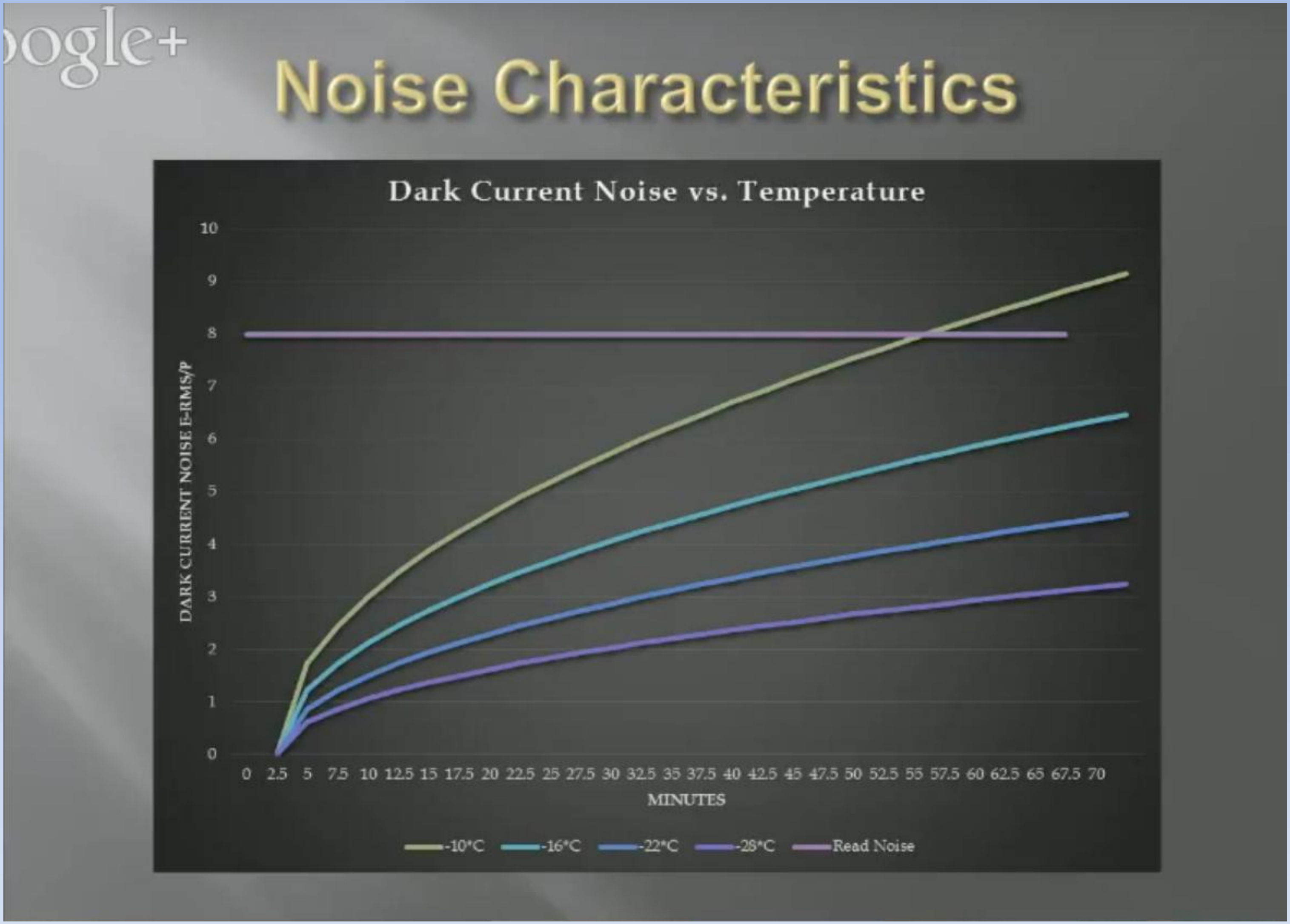
https://www.youtube.com/watch?v=LDkgcwIT-6c&app=desktop



Noise Characteristics

Temperature -10deg C

https://www.youtube.com/watch?v=LDkgcwIT-6c&app=desktop



Noise Characteristics

Dark Current Noise vs. Temperature

Sensor: KAF-8300 Temperature -10deg C

https://www.youtube.com/watch?v=LDkgcwIT-6c&app=desktop

Dark current noise will be halved every 5.7-6.1 deg C lower

Definitions

- **Full-well depth** - Each CCD is designed to hold only so many electrons within a pixel before they start to leak outwards to other pixels. This maximum size of a charge packet on the chip is called the **full well depth.** There is also a "maximum possible number" in the Analog-to-Digital converter. Most CCDs use 14-bit, 15-bit, or 16-bit A/D units: the corresponding maximum pixel values are 2^14 = 16384, 2^15 = 32768, and 2^16 = 65536.

  http://spiff.rit.edu/classes/phys445/lectures/gain/gain.html

- However, with enough signal for a given amount of time the Full-well depth can be exceeded. When that happens the image is clipped and therefore no additional info can be determined, which essentially makes the image pure white. It also reduces the dynamic range of the image. For example, this usually happens in galaxy cores and bright stars.

Definitions

- **CCD Camera Gain** - The gain of a CCD camera is the conversion between the number of electrons ("e-") recorded by the CCD and the number of digital units ("counts") contained in the CCD image.
  - Knowing the gain permits the calculation of quantities such as readout noise and full well capacity in the fundamental units of electrons.
  - The gain value is set by the electronics that read out the CCD chip. Gain is expressed in units of electrons per count.
    - For example, a gain of 1.8 e-/count means that the camera produces 1 count for every 1.8 recorded electrons.
    - Of course, we cannot split electrons into fractional parts, as in the case for a gain of 1.8 e-/count.
    - What this number means is that 4/5 of the time 1 count is produced from 2 electrons, and 1/5 of the time 1 count is produced from 1 electron.
    - This number is an average conversion ratio, based on changing large numbers of electrons into large numbers of counts.
    - Counts = "Analog-to-Digital Units" , ADU
    - Note: This use of the term "gain" is in the opposite sense to the way a circuit designer would use the term since, in electronic design, gain is considered to be an *increase* in the number of output units compared with the number of input units.

http://www.mirametrics.com/tech_note_ccdgain.php

Definitions - Vignetting

Mechanical vignetting

Mechanical vignetting occurs when light beams emanating from object points located off-axis are partially blocked by external objects such as thick or stacked filters, secondary lenses, and improper lens hoods. This has the effect of changing the entrance pupil shape as a function of angle (resulting in the path of light being partially blocked). Darkening can be gradual or abrupt – the smaller the aperture, the more abrupt the vignetting as a function of angle. When some points on an image receives no light at all due to mechanical vignetting…then this results in an restriction of the field of view (FOV) – parts of the image are then completely black.

Optical vignetting

…..caused by the physical dimensions of a multiple element lens. Rear elements are shaded by elements in front of them, which reduces the effective lens opening for off-axis incident light. The result is a gradual decrease in light intensity towards the image periphery. Optical vignetting is sensitive to the lens aperture and can often be cured by a reduction in aperture of 2–3 stops. (An *increase* in the F-number.)

Natural vignetting

……natural vignetting …..is not due to the blocking of light rays. The falloff is approximated by the $\cos^4$ or "cosine fourth" law of illumination falloff. Here, the light falloff is proportional to the fourth power of the cosine of the angle at which the light impinges on the film or sensor array. Wideangle rangefinder designs and the lens designs used in compact cameras are particularly prone to natural vignetting. Telephoto lenses, retrofocus wideangle lenses used on SLR cameras, and telecentric designs in general are less troubled by natural vignetting. A gradual grey filter or postprocessing techniques may be used to compensate for natural vignetting, as it cannot be cured by stopping down the lens. Some modern lenses are specifically designed so that the light strikes the image parallel or nearly so, eliminating or greatly reducing vignetting.

Pixel vignetting

Pixel vignetting only affects digital cameras and is caused by angle-dependence of the digital sensors. Light incident on the sensor at normal incident produces a stronger signal than light hitting it at an oblique angle. Most digital cameras use built-in image processing to compensate for optical vignetting and pixel vignetting when converting raw sensor data to standard image formats such as JPEG or TIFF. The use of offset microlenses over the image sensor can also reduce the effect of pixel vignetting.

https://en.wikipedia.org/wiki/Vignetting

Definitions

- **Read noise** is a combination of noise from the pixel and from the ADC. The Read Noise (RN) of the sensor is the equivalent noise level (in electrons RMS) at the output of the camera in the dark and at zero integration time. Note that the build up is different for a CMOS sensor and a CCD sensor. The ADC with CCD image sensors is done outside the sensor and the ADCs for a CMOS image sensor are in each pixel.

    - Read noise basically determines the contrast resolution that the camera is able to achieve. The lower the read noise level, the lower the minimum number of signal electrons that can be detected. A lower read noise means you can see smaller changes in signal amplitude, thus detect details with smaller contrast differences. Read noise is also important in combination with expressing the sensitivity of a camera. Low read noise means that you can see small contrast changes, which is typically present in scenes taken in low light conditions. A lower RN therefore results in a more sensitive sensor.

http://info.adimec.com/blogposts/read-noise-versus-shot-noise-%E2%80%93-what-is-the-difference-and-when-does-it-matter

Definitions - Optical Sensitivity - Quantum Efficiency and Read Noise

- Optical sensitivity quantifies the minimum light level which can be detected above the camera’s read noise.

- For a given exposure length, the two factors which effect sensitivity are:
  - 1) how many signal photoelectrons are generated within a pixel for a given illumination level
  - 2) how many photoelectrons needed to be reliably detected over the cameras inherent noise floor.

- The percentage of incident light which is converted into useable signal electrons is referred to as the **Quantum Efficiency or QE**. Figure 1 shows a typical CCD QE curve as a function of illumination wavelength. Unless the wavelength is specified, QE is not properly defined.

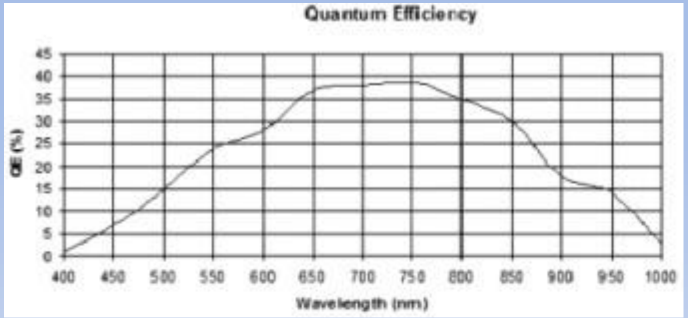
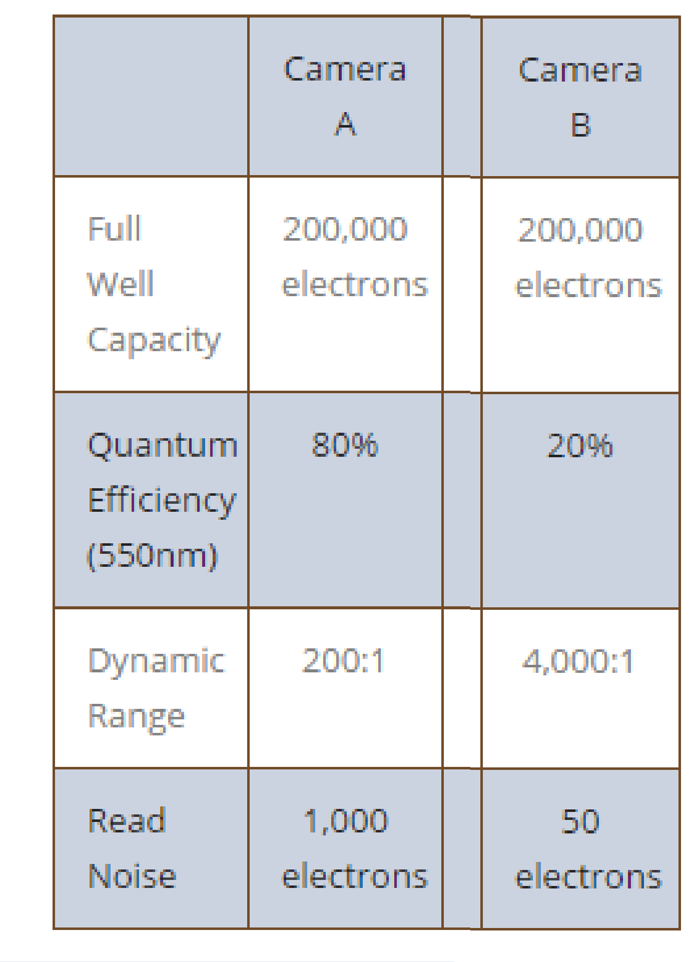


Figure 1 - Typical Quantum Efficiency Curve

http://www.quantumimaging.com/quantum-efficiency/

Definitions - Quantum Efficiency and Read Noise (Continued)



	Camera A	Camera B
Full Well Capacity	200,000 electrons	200,000 electrons
Quantum Efficiency (550nm)	80%	20%
Dynamic Range	200:1	4,000:1
Read Noise	1,000 electrons	50 electrons

- It would seem at first glance that the camera with 80% QE would be the most sensitive because it is 4 times more efficient at converting the selected wavelength of light to signal electrons.
- However, this neglects the fact that the inherent read noise floor of camera A is 1,000 electrons (200,000 electrons/200) whereas camera B has a read noise floor of 50 electrons (200,000 electrons/4,000).
- Thus, although camera A is four times more efficient in capturing the light, camera B requires 1000/50 = 20 times fewer photoelectrons to generate the same video signal.
- The end result is that the camera with four-times lower QE is actually 5 times more sensitive than the other camera!

http://www.quantumimaging.com/quantum-efficiency/

M51 QE Simulations: Rural

QE = 1

QE = 0.6

QE = 0.4

Image scale=1.5”/pixel, Seeing=2” FWHM, Read noise=8 e-, Dark current=0.05 e-/s, Exposure=60 s, Skyglow=2 e-/arcsec^2/sec

http://www.stark-labs.com

M51 QE Simulations: Urban

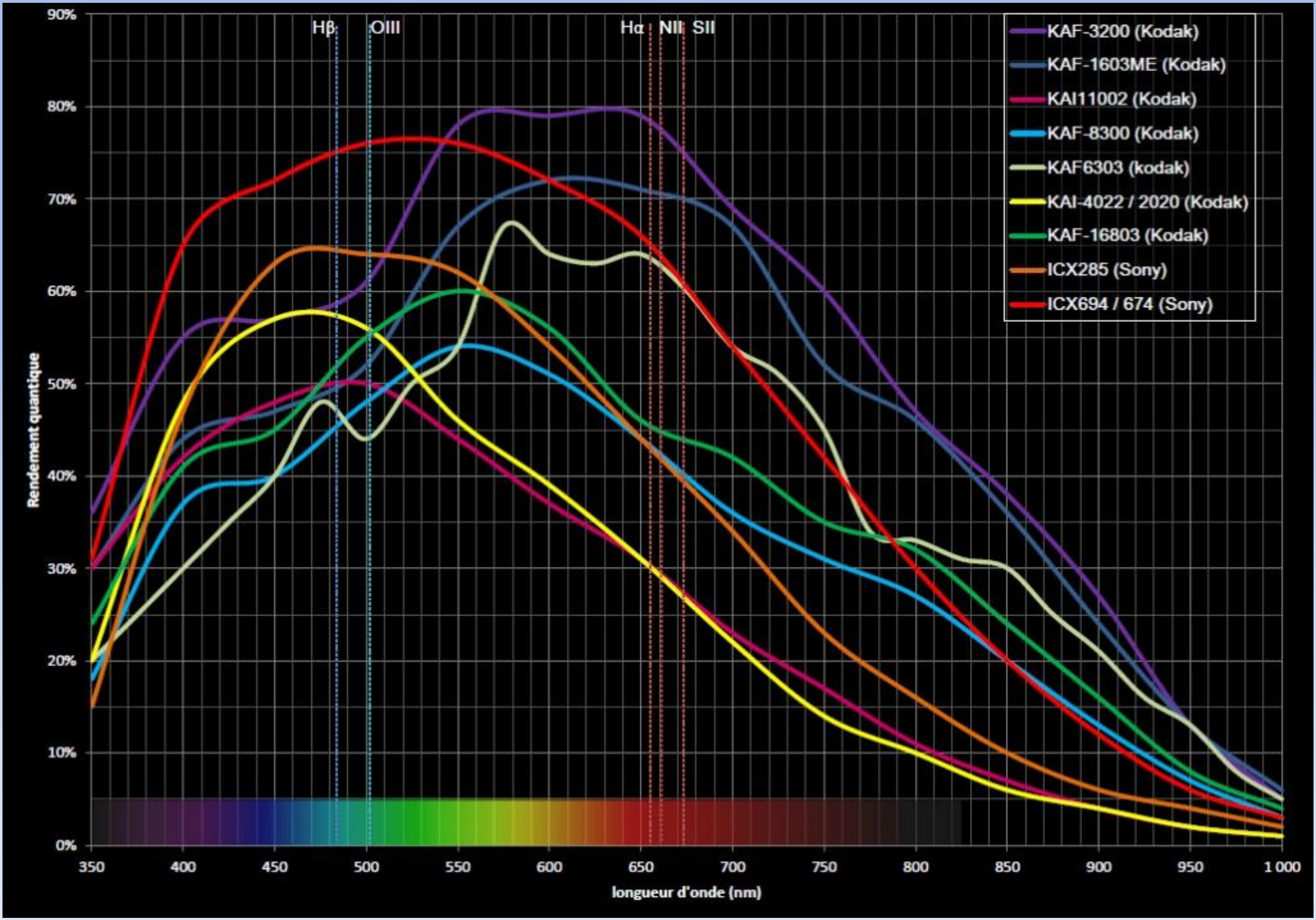
QE = 1

QE = 0.6

QE = 0.4

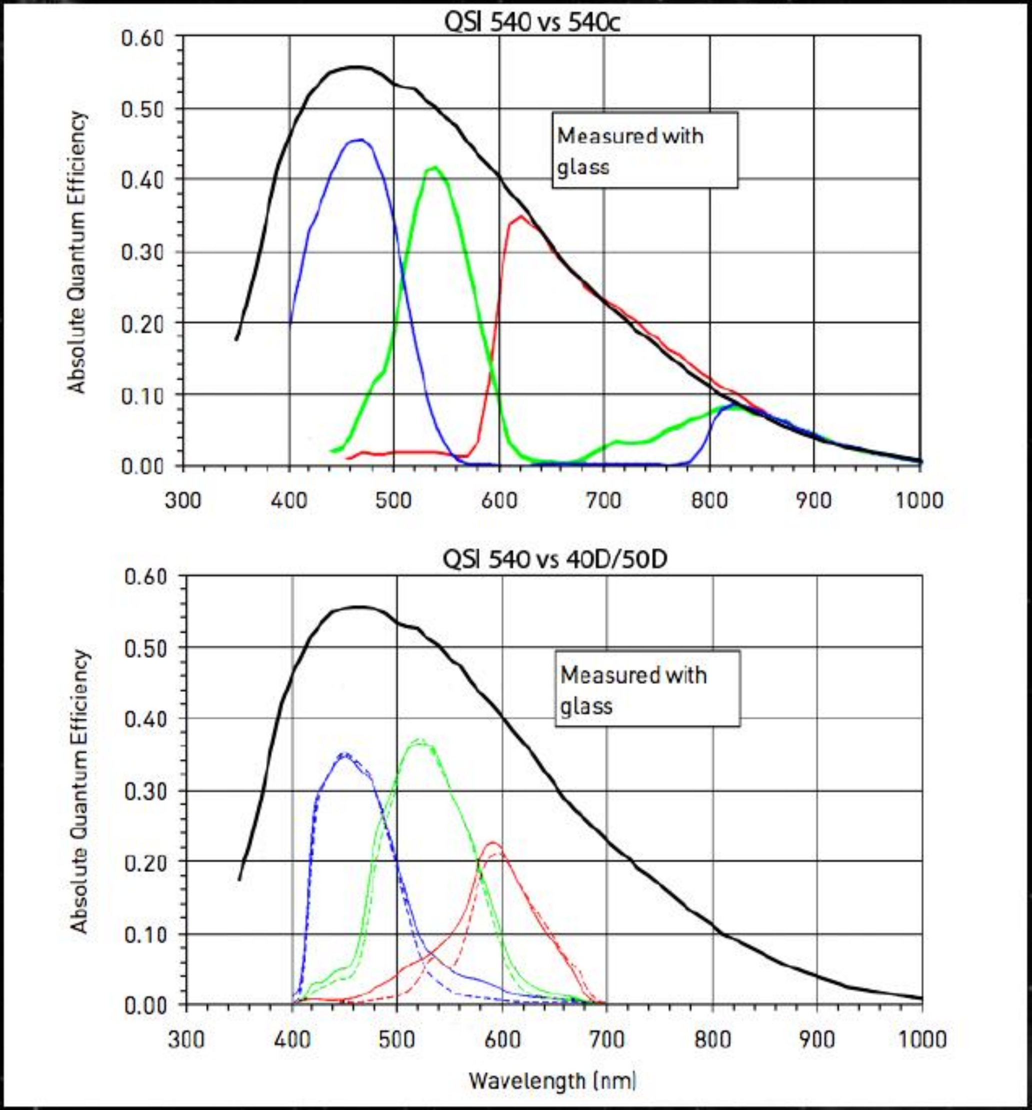
Image scale=1.5”/pixel, Seeing=2” FWHM, Read noise=8 e-, Dark current=0.05 e-/s, Exposure=60 s, Skyglow=50 e-/arcsec^2/sec

http://www.stark-labs.com



Most popular CCD's QE Comparison Chart made by Philippe Bernhard

Color vs. Mono sensors

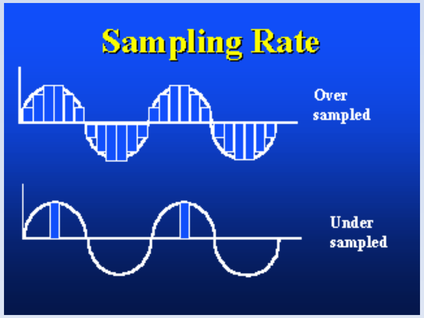


http://www.stark-labs.com

Definitions

Nyquist Sampling Theorem

Sampling a sound (using a microphone) or image (using a CCD camera) can introduce a distortion into the signal called ”aliasing.” Aliasing takes many forms; for example the apparent backward motion of wagon wheels in western movies, which occurs because the movie is actually a sequence of still frames. Nyquist showed that if the sampling rate is twice the highest frequency component, then the original information can be reconstructed without aliasing. In the case of a CCD image, you need to have a pixel density twice the highest spatial frequency in the image. In practice 2.5X is used to compensate for the distance across the diagonal of the pixel. Note that proper display of a ”critically sampled” image requires a reconstruction filter - interpolation to a higher sample rate - for proper image display. Also oversampling may be desirable because interpolation during image alignment can degrade resolution. Oversampling is also required if you intend to use deconvolution to increase resolution; the final deconvolved image must also meet the Nyquist Sampling Criterion. http://www.diffractionlimited.com/help/maximdl/Nyquist_Sampling_Theorem.htm



http://www.vanosta.be/mic_cam.htm

Other sources say that the 3-D light nyquist is 3.3 assuming a Gaussian PSD

Definitions – Fixed-pattern Noise (FPN)

- Fixed Pattern Noise (FPN), as the name implies, is noise that is in a fixed position spatially.
  - Examples of noise that are not components of FPN include read noise and Poisson noise.
- There are two primary components of FPN, Dark Signal Non-Uniformity (DSNU), and Photo Response Non-Uniformity (PRNU).
  - DSNU is a variation in the offset of the pixel value when there is no illumination (black frames).
  - PRNU is a variation in how the pixel responds to light (illuminated frames).

- **Stacking**

$$\text{Total Noise} = \sqrt{\frac{(\text{Random Noise})^2}{\text{Number of Frames}} + (\text{Fixed Noise})^2}$$

- Notice that no matter how high the Number of Frames gets, Fixed Noise cannot be eliminated.

http://www.photonstophotos.net/GeneralTopics/Sensors_&_Raw/Sensor_Analysis_Primer/Fixed_Pattern_Noise_Analysis.htm

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Capturing Faint Detail with Astrophotography

it’s…. all about the “Signal”

Capturing Faint Detail with Astrophotography

Capturing faint detail in deep-sky astronomical images is all about maximizing signal and overcoming noise. Noise comes from a variety of sources:

- Heat (dark current)
- CCD readout
- Light pollution/sky background
- Cosmic rays
- Pixel defects

How is Signal maximized?

- Travel to dark sites to reduce light pollution/sky background
- Increase image exposure duration
- Increase telescope aperture or reduce focal length
- Bin pixels
- Stack images

How is Noise minimized?

- CCDs are designed to generate low dark current
- CCD cameras are cooled to remove as much "Heat (thermal noise)" as possible
- Dark frames are used to capture the remaining dark noise and is subtracted to eliminate it from the final images (more later)
- Cameras are designed to have low readout noise.
- Travel to dark sites to help eliminate light pollution.

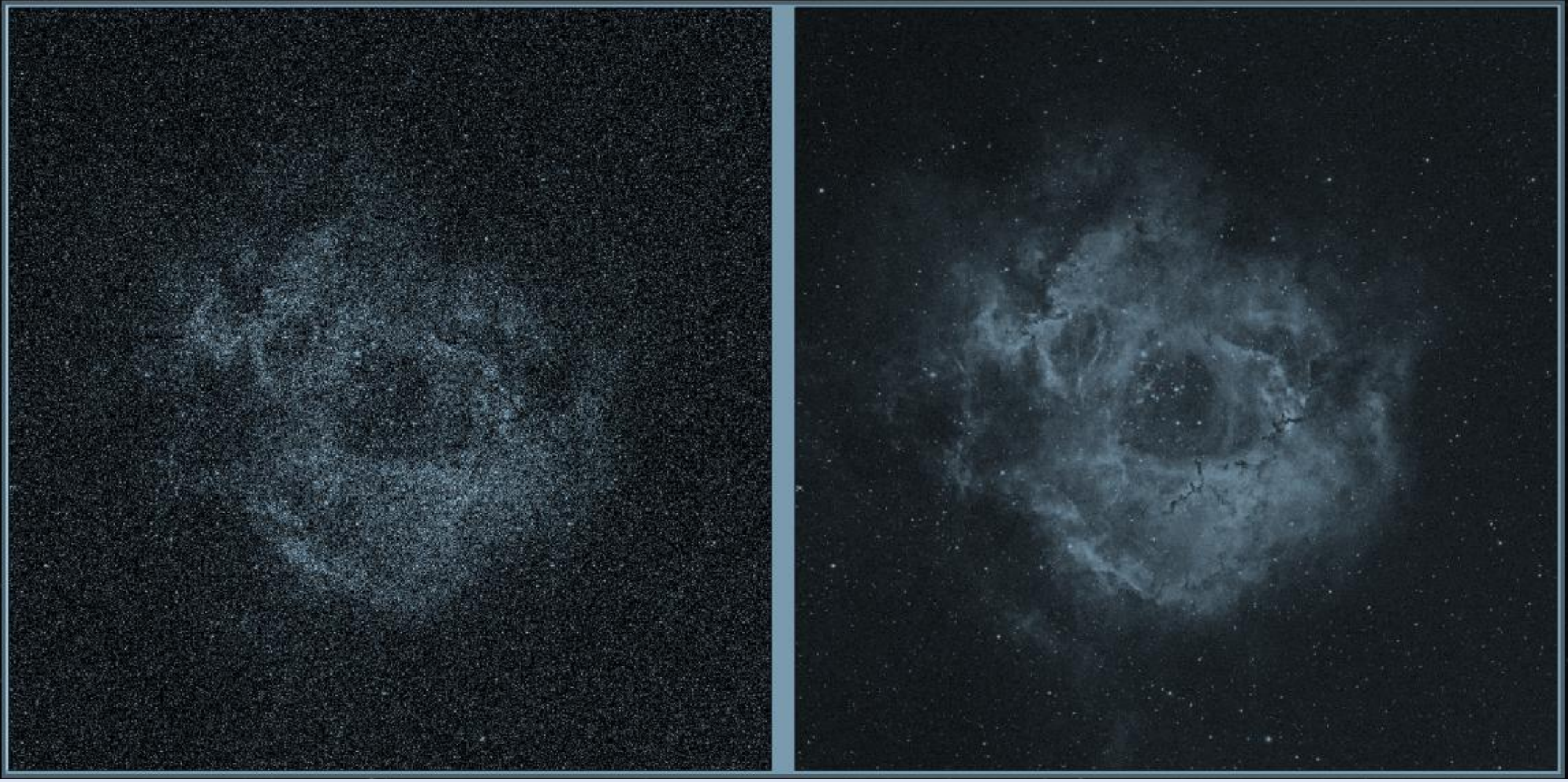
http://starizona.com/acb/ccd/advtheoryexp.aspx

Good images require good Signal to Noise (SNR) by definition

Goal: Estimate the intensity of the target and sky at each position in the image.

SNR is the ratio between the intensity of your target and the amount of noise

$$TargetPixSNR = \frac{TargetSignal}{\sqrt{TargetSignal + SkyglowSignal + DarkSignal + ReadNoise^2}}$$



SNR Criterion

The ***Rose criterion*** (named after Albert Rose) states that an SNR of at least 5 is needed to be able to distinguish image features at 100% certainty. An SNR less than 5 means less than 100% certainty in identifying image details.

https://en.wikipedia.org/wiki/Signal-to-noise_ratio

Agenda

- Astro-Photography Definitions with some examples
- Capturing Faint Detail with Astrophotography
  - Signal-to-Noise (SNR) Intro
  - Methods of Improving SNR
    - Calibration and Stacking
    - The Darker the Skies, the better the Image
  - Defining SNR with and without Stacking
  - Estimating Exposure Times and Number of Subs
  - Image Capture Strategies
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Calibration Frames

Calibrating CCD images involves removing noise artifacts and uneven illumination. This is done by taking dark frames, bias frames, and flat field images.

Calibration Images

CCD cameras are so sensitive that the heat generated by their electronics can cause noise to appear in the image. For this reason, CCD cameras are cooled, typically between 25 and 50 degrees C below ambient temperature. This minimizes the thermal noise, but in some CCDs the remaining noise is still a problem. This noise is easily eliminated by subtracting a dark frame. A dark frame is simply an image taken with the camera covered. The dark frame detects only the noise inherent in the CCD and this is then subtracted from a regular light frame. A dark must be taken at the same temperature as the light frame that it will be subtracted from, and the exposure must be of the same duration. Here is an example of a single 600-second dark frame.

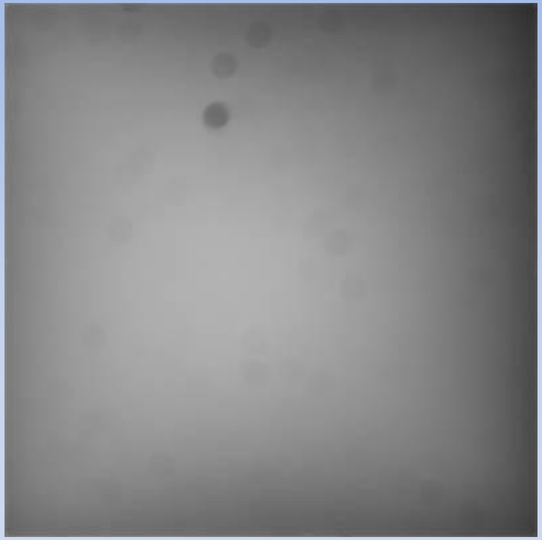
http://starizona.com/acb/ccd/software/maxim_calibrate.aspx

See more info at https://pixinsight.com/forum/index.php?topic=8839.0

Calibration Frames

Calibrating CCD images involves removing noise artifacts and uneven illumination. This is done by taking dark frames, bias frames, and flat field images.

Uneven illumination of the field normally results from vignetting in the optical system. Dust on the CCD sensor or filters can also cause dark spots in an image. These artifacts are removed using a flat field image. A flat field is simply an exposure of an evenly-illuminated light source. This is often the twilight sky, but flat field panels are also made that use artificial light sources and can be used any time. A flat field image detects the uneven illumination of the field and any dust specks. Flats are filter-dependent, so if you are using a monochrome camera with red, green, and blue filters, you must take separate flats for each filter. Below is a twilight flat field image taken through a luminance filter.



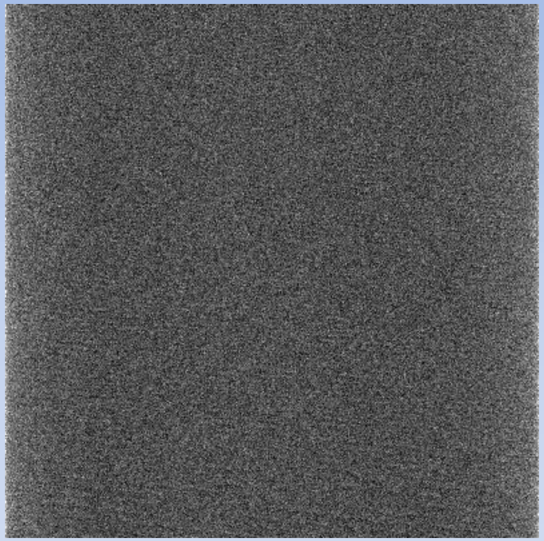
http://starizona.com/acb/ccd/software/maxim_calibrate.aspx

See more info at http://www.skyandtelescope.com/wp-content/uploads/documents/Flatfields+Mar11.pdf

Calibration Frames

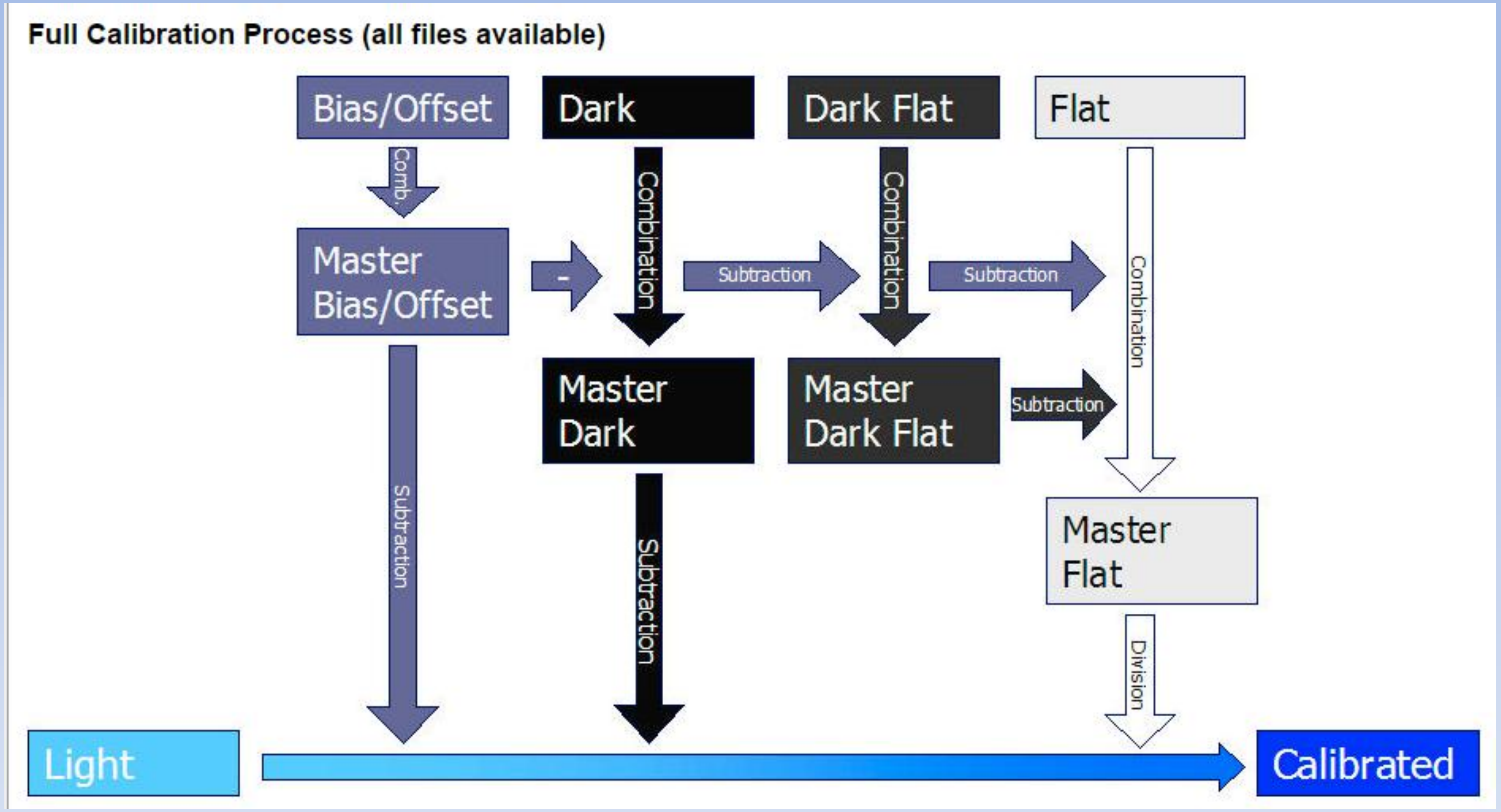
Calibrating CCD images involves removing noise artifacts and uneven illumination. This is done by taking dark frames, bias frames, and flat field images.

To properly calibrate a flat field image, another calibration image must be taken, called a bias frame. This is effectively a zero-second exposure and it detects purely the read-noise from the camera. This is noise generated when the pixels are read out of the CCD. In a low-dark-current camera, a bias will look almost just like a dark frame. This image is used to normalize the flat field. Below is a bias frame.



http://starizona.com/acb/ccd/software/maxim_calibrate.aspx

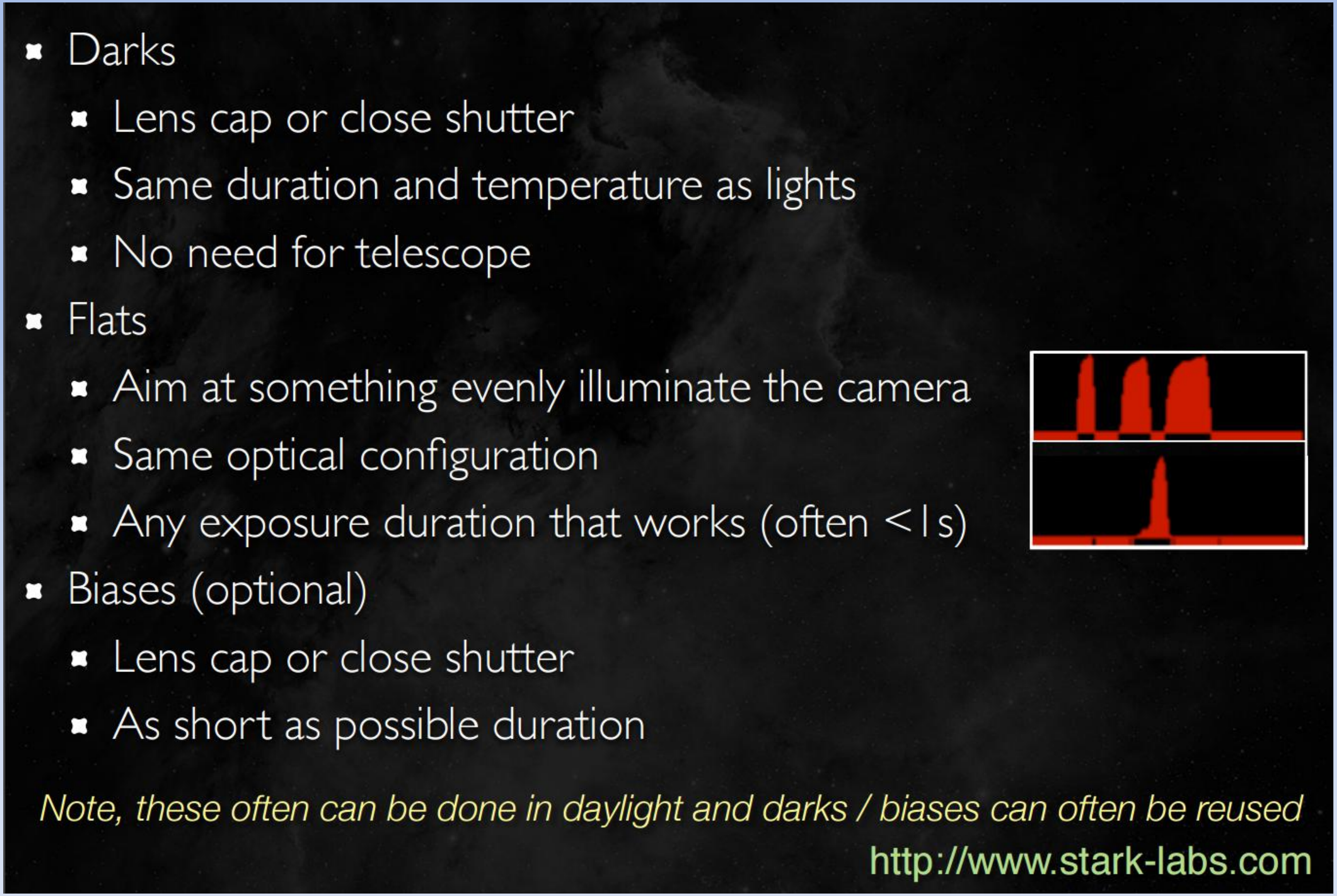
Full Calibration Process



Full Calibration Process (all files available)

http://deepskystacker.free.fr/english/index.html

Creating Calibration Frames



- Darks
  - Lens cap or close shutter
  - Same duration and temperature as lights
  - No need for telescope
- Flats
  - Aim at something evenly illuminate the camera
  - Same optical configuration
  - Any exposure duration that works (often <1s)
- Biases (optional)
  - Lens cap or close shutter
  - As short as possible duration

Note, these often can be done in daylight and darks / biases can often be reused

http://www.stark-labs.com

Flats need to taken at the deep sky focus position and through the optical train including filters. Exposure duration should be the time needed to produce about 50% of the camera full-well depth (example: 30K-32K ADU for a 16 bit camera(65535 ADU))

Calibration - The goal of pre-processing is to get the best estimate of target intensity

Total Signal(t) = Optics*Target(t) + Dark(t) + Bias
Total Noise(t) = SQRT(TotalSignal(t) + ReadNoise2)
Pixel Intensity(t) = TotalSignal(t) + TotalNoise(t)

www.stark-labs.com

Classic dark subtraction

Lights = Optics * Target(t) + Dark(t) + Bias + Noise
Darks = Dark(t) + Bias + Noise
Flats = Optics * Constant + Bias + Noise

Light - Dark = (Optics * Target(t) + Dark(t) + Bias + Noise) - (Dark(t) + Bias + Noise)
= Optics*Target(t) *+ Noise*

(Light - Dark)/(Flats - Bias) = Target(t) ***+ Noise***

From https://en.wikipedia.org/wiki/Flat-field_correction

C=(R-D)*m\(F-D) = (R-D)*G

where:
C = corrected image
R = raw image
F = flat field image
D = dark field or dark frame
m = average value of (F-D)
G = Gain = m \(F-D)

Signal/Noise Model for Stacking

Basic Signal Model

A signal can be modeled as functions consisting of both a deterministic and a stochastic component. A …. common model of many statistical systems is a signal y(t) that consists of a deterministic part x(t) added to noise which can be modeled in many situations as white Gaussian noise w(t).

$$y(t)=x(t)+w(t) \quad where \;\; w(t)\sim \mathrm{N}(0,\sigma^2)$$

White noise simply means that the noise process is completely uncorrelated.

Given information about a statistical system and the random variable from which it is derived, we can increase our knowledge of the output signal; conversely, given the statistical properties of the output signal, we can infer the properties of the underlying random variable.

Example

The signal is measured repeatedly n times and then averaged.

$$\bar{y}=\frac{1}{n}\sum_i y(t)_i = x(t)+\frac{1}{n}\sum_i w(t)_i$$

Assuming that the noise is white and that its variance is constant in time it follows by error propagation that

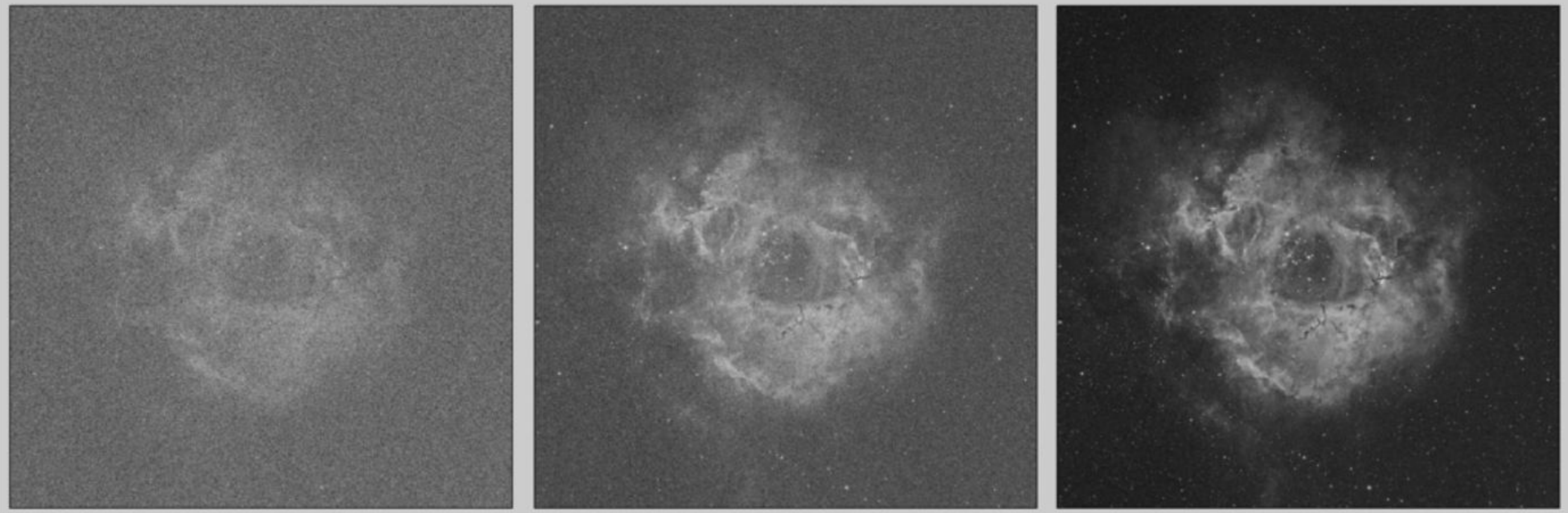
$$\sigma(\bar{y})=\frac{1}{\sqrt{n}}\sigma$$

Thus, if 100 measurements are averaged the signal to noise ratio is increased by a factor of 10, and the sigma noise reduced by 1/10.

https://en.m.wikipedia.org/wiki/Statistical_signal_processing

We stack many images to reduce noise

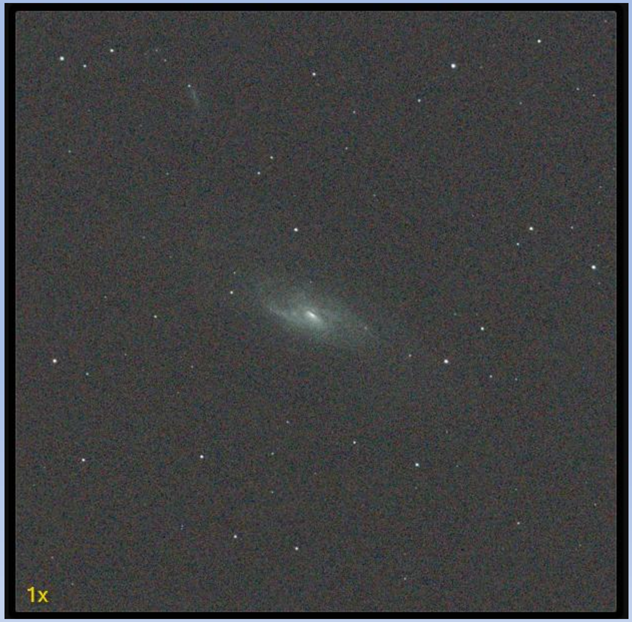
Noise (ideally) goes down by sqrt(#Samples)

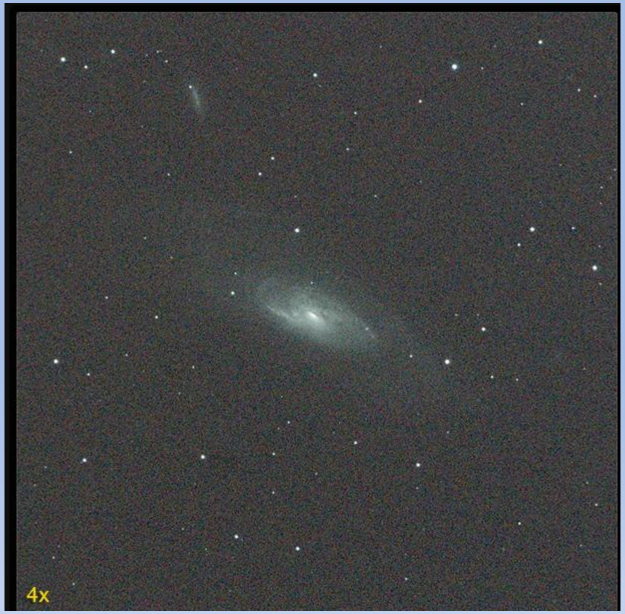


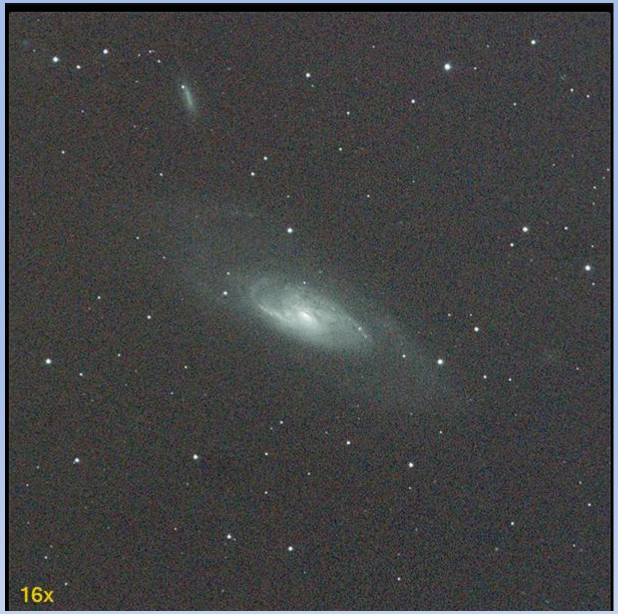
1 Image	10 Images	100 Images
Noise=100	Noise=37	Noise=10

http://www.stark-labs.com

Stacking Images Example







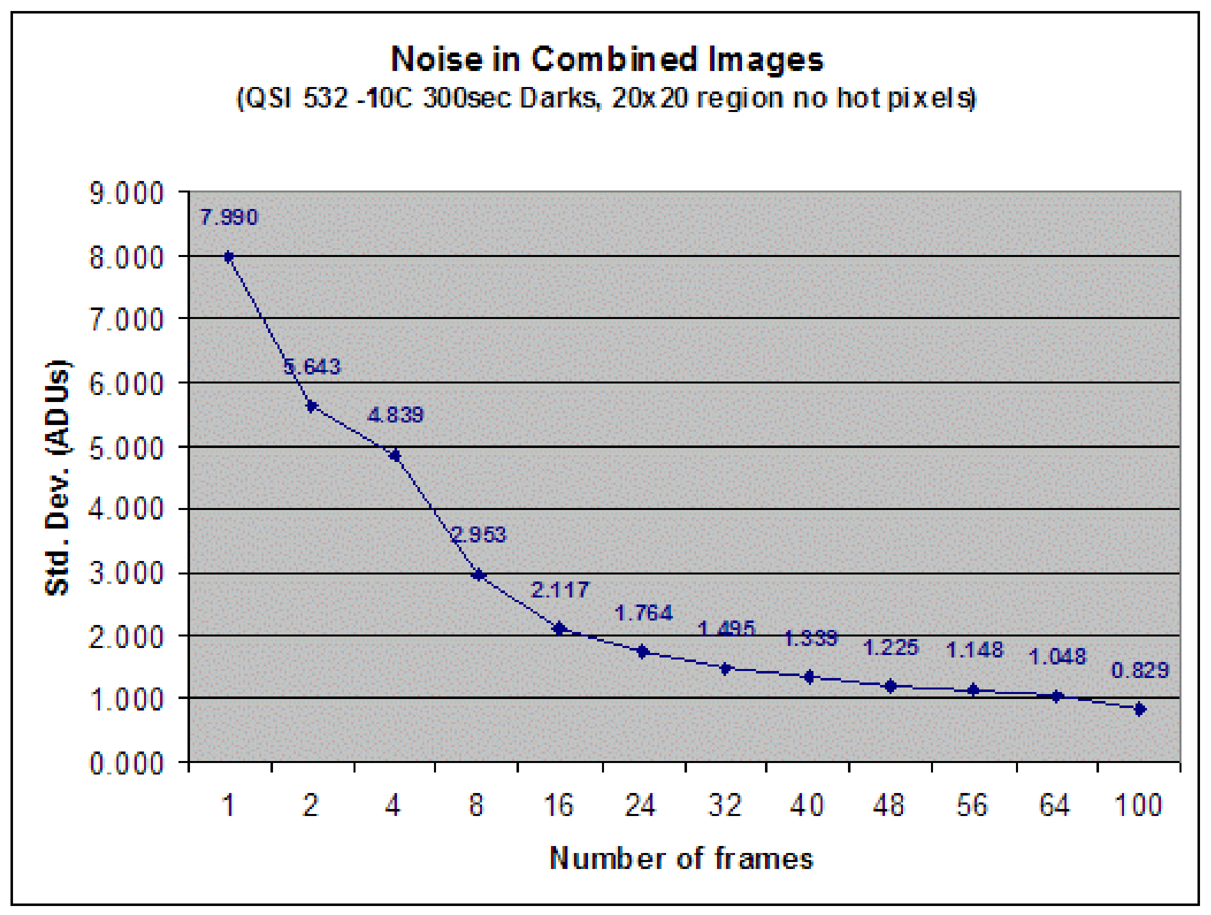
https://jonrista.com/the-astrophotographers-guide/astrophotography-basics/snr/

Reduce Noise by Dark Frame Subtraction with Stacking

SNR of Combined Dark Frames

When you subtract a dark frame from a light frame to remove the contribution of dark current, you are necessarily *adding* a small amount of noise. The question of, "how many dark frames do I need" comes down to how little noise do you wish to add to your light frames.

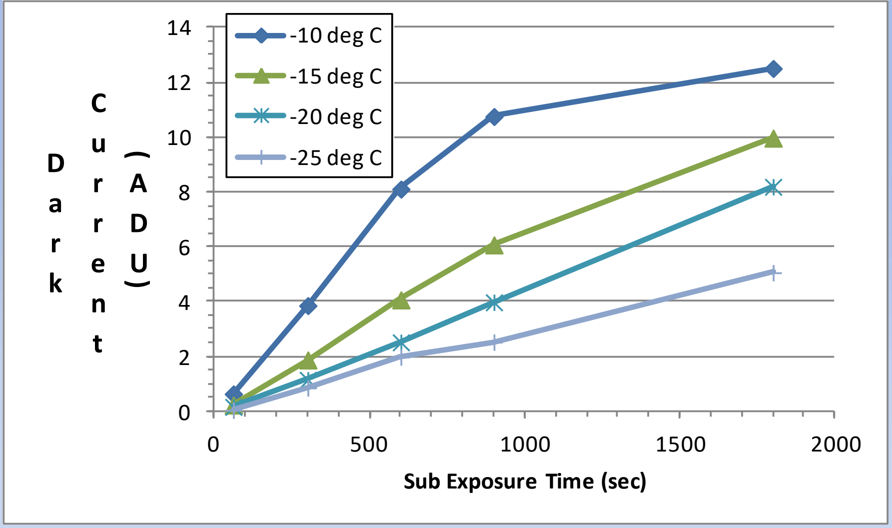
Below is a graph that plots the standard deviation (noise) of background values in a master dark frame produced by combining from 1 to 100 individual 5-minute dark frames captured at -10C with a QSI 532.

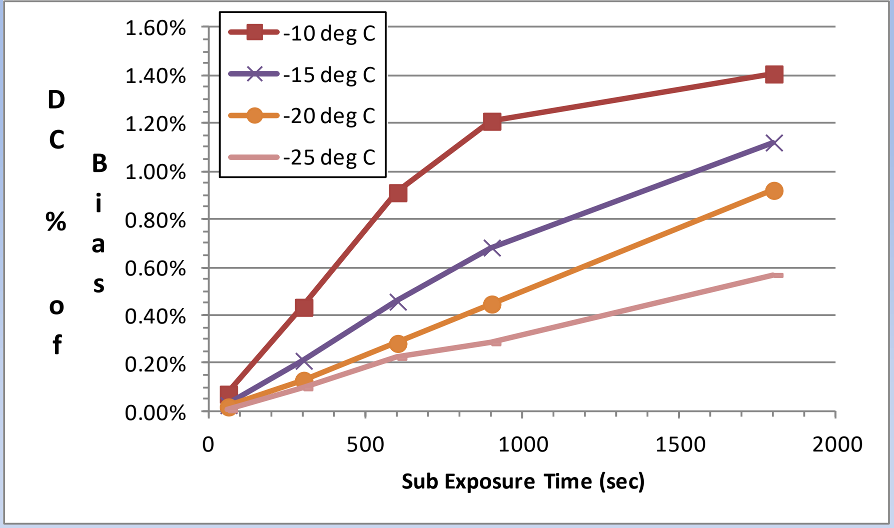


http://www.qsimaging.com/combined-darks-snr.html

At Camera read noise < ~10 photons, the effect of Subtracting darks may become unnecessary!

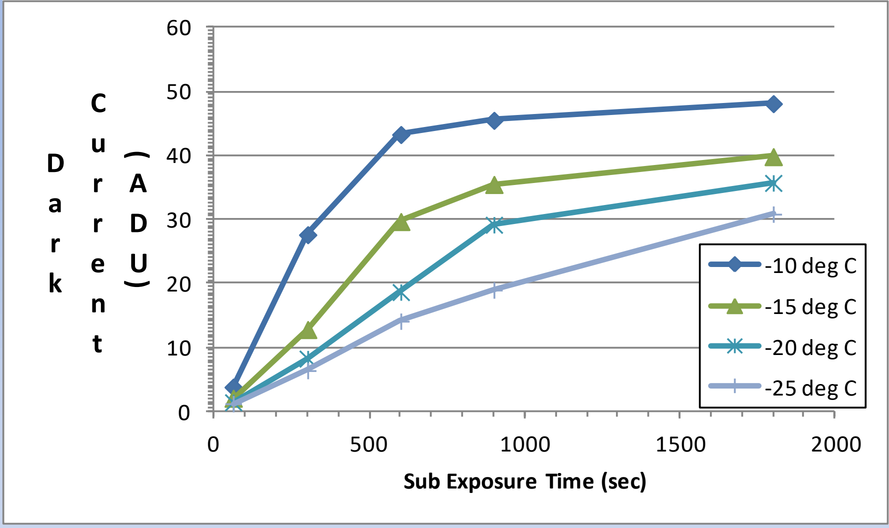
SBIG STF-8300 Low Dark Current (DC) Suggests Darks may not be necessary at all temperatures and Exposure Times

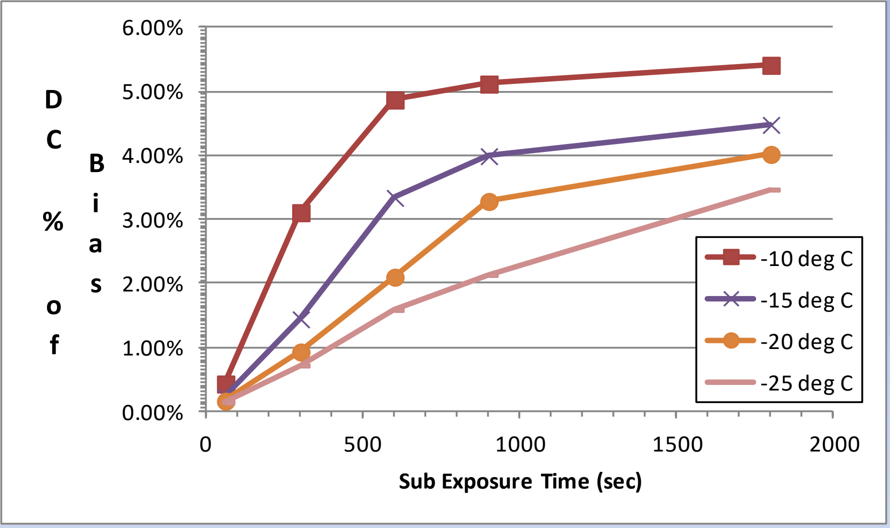




- Camera SBIG STF-8300 (Read Noise 9.3e-)
- Dark Current = Master Dark – Master Bias
    - Master Darks from 16 Subs
    - Master Bias from 256 Subs
- PixInsight Linear Fit of Master Darks/Bias to
    - Master Dark, -10C, 1800s

SBIG STF-8300 Bin 2 Low Dark Current (DC) Is 4x higher than Bin 1, But also suggests Darks may not be necessary at all temperatures and Exposure Times





- Camera SBIG STF-8300
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  - Master Bias from 256 Subs
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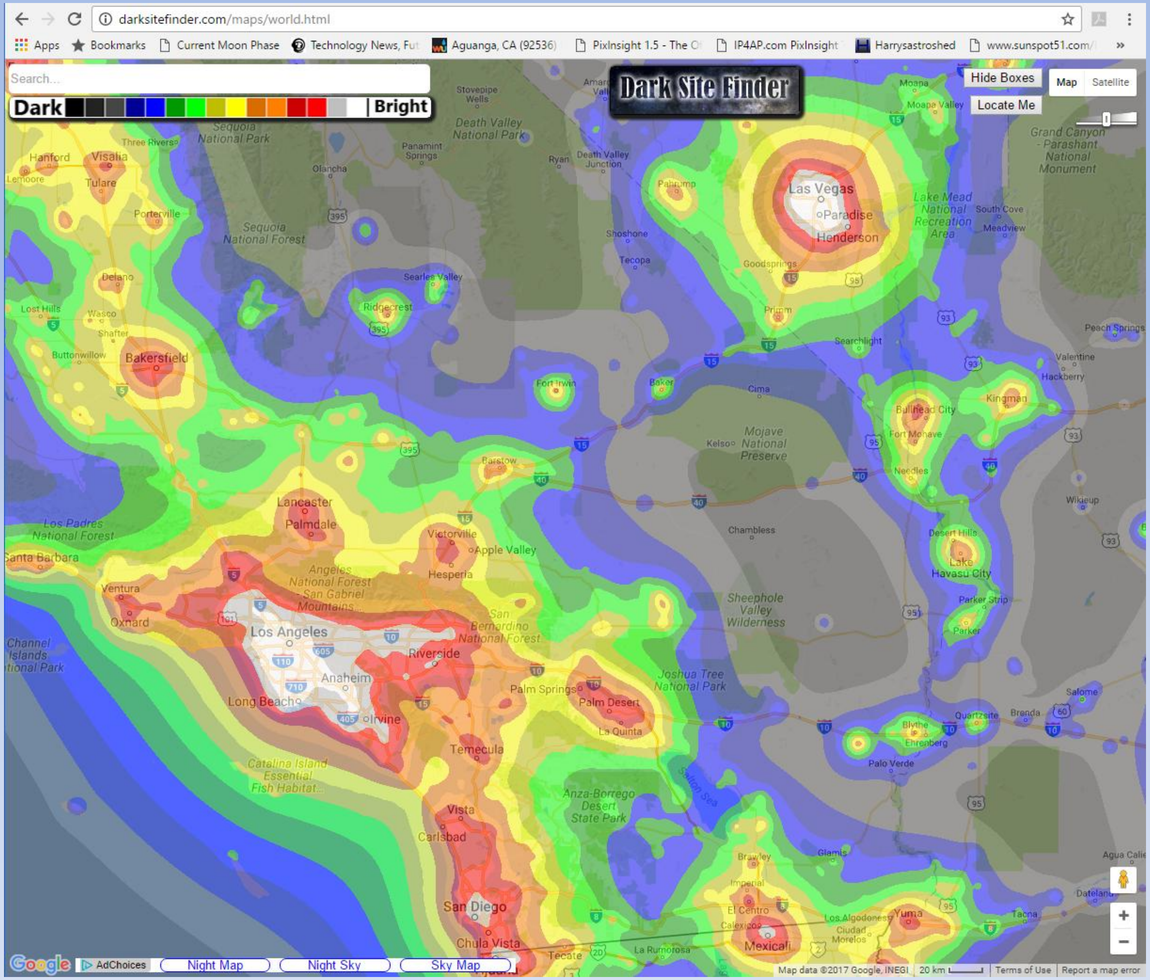
Dark site Map



The Darker the Skies, the better the Image. Several sources to determine the light pollution in your observing area are listed below.

- www.cleardarksky.com
- DarkSiteFinder.com/maps/World.html

As of 2006

Estimating Sky Background - Example

- According to www.stsci.edu/instruments/observatory/PDF/SCS8.rev.pdf, the flux of a magnitude 0 object at 5483A = 3.67×10^{-9} erg s^{-1} cm^{-2} A^{-1}.

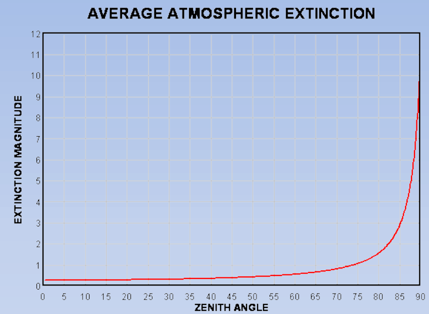
Converting to JanSkys = $3.67 \times 10^{-9} * 3.34 \times 10^{4} * 5483^{2}$ = 3685 JanSkys

Converting to photons s^{-1} cm^{-2} A^{-1} = 3685*1.51x103/5483 = 1.015×10^{3} photons s^{-1} cm^{-2} A^{-1}

Assuming filter bandwidth of 1000A, therefore

Flux = 1.015×10^{3} photons s^{-1} cm^{-2} A^{-1}. *1000 = 1.015×10^{6} Photons s^{-1} cm^{-2}.

- From Clearskies
  - Limiting magnitude = 21.25-21.51 mag/arc-sec^{2}
  - Atmospheric Extinction from Sky&Telescope Spreadsheet
    (http://www.skyandtelescope.com/astronomy-resources/transparency-and-atmospheric-extinction/)
    - 90deg elevation = 0.23 mag
    - 43deg elevation = 0.33 mag (Lowest M74 elevation during sub)
  - Corrected Limiting magnitude 21.25-0.33 = 20.92 mag/arc-sec^{2}



http://www.asterism.org/tutorials/tut28-1.htm

Sky is dimmer than mag 0 by $1/2.512^{20.92} = 1/2.335666 \times 10^{8} = 4.28 \times 10^{-9}$

Photons = 1.015×10^{6} Photons s^{-1} cm^{-2}/ 2.335666×10^{8} = 4.35×10^{-3} Photons s^{-1} cm^{-2} arc-sec^{-2}

- Telescope Aperture area = $\pi r^{2} = \pi ((30.5cm/2)^{2} - (14.92cm/2)^{2})$ = 555.78 cm2
  - Photons entering aperture = 555.78 cm2 * 4.35×10^{-3} Photons s^{-1} cm^{-2} arc-sec^{-2}= 2.42 Photons s^{-1} arc-sec^{-2}
- Accounting for Camera Gain = 0.37 e-/ADU and converting to minutes
  - 60s/min*2.42 Photons s^{-1} arc-sec^{-2}/0.37e-/ADU = 392.05 ADU min^{-1} arc-sec^{-2}

Estimating Sky Background – Example (continued)

- Light traveling through the telescope optics and being counted by the detector will be reduced by
  - **About 10% of the light is lost with each reflection due to vignetting, or the shadowing of the primary mirror by the secondary and its support structure.
  - **Approximately another 10% of the photons are lost at each reflection due to imperfect reflectivity of the mirrors from the combination of material limitations and dust.
  - **About 10% of the light is lost going through filter
  - Detector QE = 0.47
- Total end-to-end throughput of $(0.9*0.9)^2*0.9*0.47 = 0.59*0.47 = 27.75\%$

- Background flux = 0.2775* 392.05 ADU min^{-1} arc-sec^{-2} = 108.79 ADU min^{-1} arc-sec^{-2}

- Background flux recorded on a pixel
  - Image Scale = 206.265*Pixel(microns)/FocalLength(mm)=206.265*5.4/1700=0.66 arc-sec
  - Camera pixel area = (0.66 arc-sec)^2
  - Background flux/pixel = (0.66 arc-sec)^2* 108.79 ADU min^{-1} arc-sec^{-2} =47.39 ADU/min

- Actual Measured Background flux/pixel = 94-140 ADU/min

**“Estimating Exposure Times”, Brian Keeney, 9/28/2006

Methods of Improving SNR - Summary

- Calibrating CCD images involves removing noise artifacts and uneven illumination. This is done by taking dark frames, bias frames, and flat field images.

- Stacking is used to increase the signal to noise ratio

  The signal is measured repeatedly n times and then averaged.

$$\bar{y} = \frac{1}{n}\sum_i y(t)_i = x(t) + \frac{1}{n}\sum_i w(t)_i$$

  Assuming that the noise is white and that its variance is constant in time it follows by error propagation that

$$\sigma(\bar{y}) = \frac{1}{\sqrt{n}}\sigma$$

  Thus, if 100 measurements are averaged the signal to noise ratio is increased by a factor of 10, and the sigma noise reduced by 1/10.

- With the SBIG STF-8300 low dark current (DC) and read noise < ~10 photons, data suggests that calibration Darks may not be necessary at all temperatures and Exposure Times

Methods of Improving SNR – Summary (continued)

- The Darker the Skies, the better the Image. Several sources to determine the light pollution in your observing area are listed below.
  - **www.cleardarksky.com**
  - **DarkSiteFinder.com/maps/World.html**
- Example was provided on how to estimate the sky background flux and compare to measurement.

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Defining Signal-to-Noise ratio

DEFINING SNR

The most basic signal-to-noise ratio formula is as follows:

SNR = S/N

where S is the signal and N is the noise.

The noise itself in a pure signal, therefore: N = SQRT(S)

Which means our SNR formula is really: SNR = S/SQRT(S)

However, the signal is really made up of several terms, Target object, Sky background and DC, which are all a function of time.

$S(t) = S_{TARGET}*t + S_{sky}*t + DC*t$

The only signal that we really want is the target object (S_{TARGET}) signal, but unfortunately we also receive a signal from the sky (S_{sky}), and the electronic camera creates a Dark Current (DC) signal.

https://jonrista.com/the-astrophotographers-guide/astrophotography-basics/snr/

Defining SNR – Dark Current

Dark current arises from thermal generation of electrons in the CCD – once we start counting electrons, there is no way to distinguish between those arising from photon hits (the "good" ones) and those generated thermally (the "bad" ones).

- It is a slow and steady accumulation of charge in the pixels due to leakage current. Without anything to suppress it, a long enough dark frame exposure would eventually clip out to pure white, as that slow accumulation of charge would eventually saturate the pixels.

- Dark current is quite sensitive to temperature, so most astronomy cameras are operated at temperatures well below the ambient temperature in order to minimize it.
- Dark current is relatively small for most such cameras, but it's never zero and it must be taken into account for SNR calculations.

- While the sensor circuitry will remove the dark current offset for us, it's noise cannot be removed. That noise will show up as increased random noise relative to the square root of the dark current, and it will show up as hot pixels, as each pixel will respond to leakage current a little differently. Most pixels will experience the average amount of current leakage, some will experience a little less or a little more, and a few will experience significantly less or significantly more. This leads to hot and cold pixels, and is the primary reason we use dark frame subtraction.

https://jonrista.com/the-astrophotographers-guide/astrophotography-basics/snr/

"SNR for Non-Engineers", Bruce Waddington , November 2009

Combining Dark Current Noise

So each of the signal levels we measure, including object signal, sky background signal, and dark current signal, has a corresponding noise level. For relatively low signal counts, the counting rates have a Poisson distribution, which means that the associated measurement uncertainty (noise) is given by √ (Signal Count). These uncertainties will propagate in a well-known form as we add or subtract signal levels:

For the quantity (A – B) or (A + B), the resultant uncertainty will be $\sqrt{(\sigma_a^2 + \sigma_b^2)}$

So this will be the common form of the noise term we use in the denominator of any of our SNR calculations, and most of our analysis will involve computing what these terms are and looking at their relative magnitudes.

$$Noise = \sqrt{\left[\left(\sqrt{(t * S_{Target})}\right)^2 + \left(\sqrt{(t * S_{Sky})}\right)^2 + \left(\sqrt{(t * DC)}\right)^2\right]} = \sqrt{t * \left(S_{Target} + S_{Sky} + DC\right)}$$

“SNR for Non-Engineers”, Bruce Waddington , November 2009

Additional Noise – Read Noise

Unfortunately, there are several additional noises that must included. Only one will be considered at this time: Readout noise.

- Readout noise is generated by the CCD when the data from the chip is transferred to the computer adding the same amount of read noise to every sub exposure frame you acquire. This is a measurable quantity and is quoted by CCD manufacturers in the spec sheets for their products. For example the SBIG STF-8300 has a readout noise of 9.3e-.
- Read noise differs from dark noise in that it doesn't have a "signal" associated with it. It is primarily dependent on the design of the camera rather than the behavior of the detector, but it is still a statistical quantity associated with counting events. But we are given this noise parameter explicitly, as an average value in units of electrons/pixel, unlike the dark noise term. For most astronomy cameras, the read noise contributes more to the noise denominator than dark noise, and for short exposures, it can be the largest noise term of all.
- Read noise is also a Poisson uncertainties, so the value we estimate by the respective signal level. The read noise term, however, is a directly measured (or vendor-supplied) value so we will use "R" rather than $\sigma_{\text{read noise}}$.
- Note at www.stark-labs.com, there is a article on how to measure your specific camera errors.

http://starizona.com/acb/ccd/advtheoryexp.aspx
"SNR for Non-Engineers", Bruce Waddington , November 2009

Combining Read Noise

Now, we need to combine these two sources of noise. We do that by taking the square root of each of them squared. So, we have sqrt(sqrt(Total_Signal)2 + Read_Noise2) which simplifies to:
Noise = sqrt(Total_Signal + Read_Noise2)

So our final Noise for one pixel is,

$$Noise = \sqrt{\left(\left(\sqrt{t*\left(S_{Target}+S_{Sky}+DC\right)}\right)^2+\left(\sqrt{R_{Noise}^2}\right)^2\right)} = \sqrt{t*\left(S_{Target}+S_{Sky}+DC\right)+R_{Noise}^2}$$

Signal to Noise Part 2: Understanding One Pixel (May 26, 2009, Cloudy Nights) PDF Reprint, author: Craig Stark, Stark-labs

SNR

Reviewing…..the SNR equation is Signal/Noise

We defined the noise and now we must add the signal equation to the numerator. However, we don't use the signal that was used to define the noise. We are only interested in the signal from the target, because we want the signal-to-noise to be defined with respect to the target signal.

$$SNR = \frac{t * S_{Target}}{\sqrt{\left(\left(\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right)}\right)^2 + \left(\sqrt{R_{Noise}^2}\right)^2\right)}} = \frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^2}}$$

Verification that noise is square root of signal

Two algorithms used to generate Poisson random numbers: Fortran and Excel

- Fortran generated from 30 to 1,000,000 random Poisson numbers
- Excel generated from 30 to 30,000 random Poisson numbers

	Fortran		Excel		Excel		Excel		Excel	
	Mean = 9		Mean = 9		Mean = 360		Mean = 720		Mean = 1440	
Samples	Calc Mean	Calc SD	Calc Mean	Calc SD	Calc Mean	Calc SD	Calc Mean	Calc SD	Calc Mean	Calc SD
30	8.733	4.017	8.833	2.547	353.967	16.633				
50	8.76	3.783	8.143	2.525	357.44	19.264				
100	8.82	3.488	8.424	2.868	359.94	21.713				
300	8.913	3.177	8.579	3.052	359.923	20.064				
500	8.918	3.089	8.749	3.063	360.796	18.996				
1000	8.964	3.059	8.837	3.053	360.622	19.119				
3000	8.954	3.012	8.998	3.076	360.502	18.893				
5000	8.976	3.029	8.931	3.063	360.396	19.03				
10000	8.976	3.018	8.957	3.053	360.112	19.151	720.209	26.524	1440.222	38.032
20000	8.982	2.999	8.961	3.011	360.035	19.112				
30000	8.98	2.991	8.971	3.006	359.929	19.064				
50000	8.988	2.997								
100000	8.993	2.998								
500000	8.999	3.004								
1000000	8.997	3.002								

- The two models agree closely
- Noise is square root of signal at about 1000 samples
  - Need about 30x30 pixels to get reliable noise estimate
- Doubling the signal, increases 1 sigma noise by about sqrt(2)
- Higher the signal, the ratio of noise to signal become smaller

Noise Variations by Signal

Applying the fact, that 1 sigma noise is the square root of the signal, how large does signal need to be to produce different ratios of noise to signal?

Poisson mean	sqrt(mean) sigma value	Sigma to Mean ratio	3 Sigma to Mean ratio
9	3.0	0.333	1.000
27	5.2	0.192	0.577
45	6.7	0.149	0.447
90	9.5	0.105	0.316
135	11.6	0.086	0.258
180	13.4	0.075	0.224
270	16.4	0.061	0.183
300	17.3	0.058	0.173
400	20.0	0.050	0.150
600	24.5	0.041	0.122
800	28.3	0.035	0.106
1,000	31.6	0.032	0.095
2,000	44.7	0.022	0.067
3,000	54.8	0.018	0.055
5,000	70.7	0.014	0.042
10,000	100.0	0.010	0.030
15,000	122.5	0.008	0.024
20,000	141.4	0.007	0.021
30,000	173.2	0.006	0.017
50,000	223.6	0.004	0.013
80,000	282.8	0.004	0.011
100,000	316.2	0.003	0.009

- Need a signal of 10,000 to produce 1% 1 sigma noise
- Need a signal of about 90,000 to produce 1% 3 sigma noise

- A signal of 300, produces a 3 sigma noise of about 17%
- A signal of 90, almost doubles the 3 sigma noise at 32%

So how to reduce noise?

Improving SNR by Image Stacking

One method of improving SNR is by stacking images. For example, lets take several image exposures (subs) of the same duration and combine.

Remember that SNR = S/sqrt(S).
What happens if we stack two images together,

$$SNR = \frac{2S}{\sqrt{2S}} = \frac{2S}{1.414\sqrt{S}} = \frac{1.414S}{\sqrt{S}} = \sqrt{2}\ \frac{S}{\sqrt{S}}$$

So Stacking two images increases the SNR of a single image by SQRT(2)

- Increasing signal faster than noise, effectively reduces noise in comparison to signal

Therefore, the general equation for stacking images is SQRT(N), where N is number of images

So our SNR equation becomes,

$$SNR = \frac{N * t * S_{Target}}{\sqrt{N * \left(t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}\right)}} = \frac{N}{\sqrt{N}}\ \frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

$$SNR = \sqrt{N}\ \frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

Note this equation assumes images are stacked using Mean or Average Image Combine

How to use the SNR Equation

$$SNR = \sqrt{N}\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^2}}$$

- Suppose, we point the telescope at a galaxy, M74, and take a several minute test sub. We then measure the raw intensity in ADU of M74. The ADU value that is obtained contains values from M74, the sky background and DC current.
- But we can also measure the average sky background around M74. The Sky background intensity also includes DC current. So if we subtracted the Sky background intensity from the M74 intensity, we end up with only the M74 intensity or signal. Note that the measured ADU of the image needs the calibration bias to be subtracted to be correct, however, (target – bias) – (Sky – bias)= target – sky = S_{Target}
- Taking the average sky background ADU measurement and subtracting the calibrated Dark, we get Ssky. Note that the Calibrated Dark already has Bias in it, so subtracting also removes the Bias from the Sky background.
- Take the calibrated dark and subtract the calibrated bias to obtain DC. Note the calibrated dark and bias needs to be the same overall intensity. Dark ADU must be greater than bias ADU.
- Calibrated dark and bias can be obtained from master dark and bias and must be equivalent to the duration, temperature and binning of the target image.

SNR Equation Summary

$$SNR = \sqrt{N}\,\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

SNR – Signal-to-Noise Ratio
N – number of subs of equal duration, equal temperature and binning
t – multiples of Sub duration, equivalent to minutes if sub duration is 1 minute
Starget – Target signal with sky background (Including DC and bias) removed
Ssky – Sky signal with DC (Including bias) removed
DC – Dark Current with Bias removed
Rnoise – Camera Read Noise

$$\begin{aligned} where\ \ S_{Target} &= \mathrm{Target} - Sky \\ S_{Sky} &= Sky - Dark \\ DC &= Dark - Bias \end{aligned}$$

Note:

- All values must be consistent with either using ADU or e-.
- Converting ADU to e-, requires ADU to be multiplied by Camera Gain.
- Some software add a value to the ADU as a bias, such as 100, may sure to subtract the value from your measured image ADU if it applies

CCD SNR Calculator spreadsheet can be downloaded at
http://www.stark-labs.com/craig/articles/articles.html,
(Described in Part 2 of the Cloudy Nights SNR series).

Image Combine Methods

Image Combine Methods consist of two distinct parts: Rejection and combination

According to PixInsight, Pixel Rejection

“the set of integrated images usually contains spurious data that cannot be characterized as random noise. Here we are interested in accidental phenomena such as plane or satellite trails and cosmic ray impacts on CCD and CMOS sensors, and also in instrumental defects such as hot or cold pixels and bad pixel rows and columns (with the necessary help of some dithering between subexposures!). All of these *bad data* form bright or dark artifacts at relatively small dimensional scales, which can be removed efficiently during the image integration task thanks to a family of statistical methods collectively known as *pixel rejection algorithms*.

The goal of a pixel rejection algorithm is to exclude outliers from the set of pixels that are to be combined in each pixel stack. The differences between the rejection algorithms available lay basically in their sophistication and suitability to detect true outliers in small and large sets of images.”

https://pixinsight.com/doc/tools/ImageIntegration/ImageIntegration.html#description_003

According to PixInsight, Combination

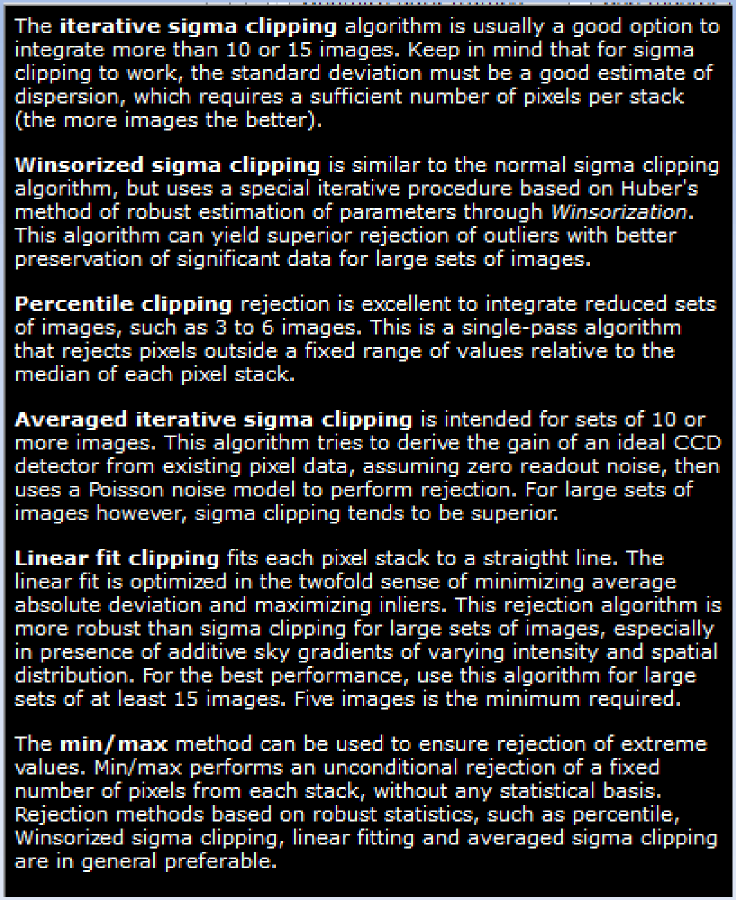
“The image integration process combines the components of each pixel stack into one pixel of an *integrated image*. Since our main goal is to improve the signal-to-noise ratio (SNR) in the integrated result, we are interested in knowing the SNR increments that can be achieved with different pixel combination operations.”

https://pixinsight.com/doc/tools/ImageIntegration/ImageIntegration.html#description_001

Image Combine Methods

Different Software programs handle Image Combine methods differently. Maxim DL allows a user to select an algorithm that does both rejection and combine. While PixInsight allow a user to select the rejection and combine methods independently. PixInsight combine methods include Average, Median, Min and Max.

PixInsight Rejection Algorithms



The **iterative sigma clipping** algorithm is usually a good option to integrate more than 10 or 15 images. Keep in mind that for sigma clipping to work, the standard deviation must be a good estimate of dispersion, which requires a sufficient number of pixels per stack (the more images the better).

Winsorized sigma clipping is similar to the normal sigma clipping algorithm, but uses a special iterative procedure based on Huber's method of robust estimation of parameters through *Winsorization*. This algorithm can yield superior rejection of outliers with better preservation of significant data for large sets of images.

Percentile clipping rejection is excellent to integrate reduced sets of images, such as 3 to 6 images. This is a single-pass algorithm that rejects pixels outside a fixed range of values relative to the median of each pixel stack.

Averaged iterative sigma clipping is intended for sets of 10 or more images. This algorithm tries to derive the gain of an ideal CCD detector from existing pixel data, assuming zero readout noise, then uses a Poisson noise model to perform rejection. For large sets of images however, sigma clipping tends to be superior.

Linear fit clipping fits each pixel stack to a straigth line. The linear fit is optimized in the twofold sense of minimizing average absolute deviation and maximizing inliers. This rejection algorithm is more robust than sigma clipping for large sets of images, especially in presence of additive sky gradients of varying intensity and spatial distribution. For the best performance, use this algorithm for large sets of at least 15 images. Five images is the minimum required.

The **min/max** method can be used to ensure rejection of extreme values. Min/max performs an unconditional rejection of a fixed number of pixels from each stack, without any statistical basis. Rejection methods based on robust statistics, such as percentile, Winsorized sigma clipping, linear fitting and averaged sigma clipping are in general preferable.

Maxim DL

Sum – the image pixels are simply added together.
Average – same as sum except the result is divided by the number of images used.
Median – the median or middle value from all the images is taken. This strongly suppresses outlier pixels but is not as good at removing random Gaussian noise.
Sigma Clip – a compromise between Average and Median. A standard deviation is calculated for each pixel location. The pixel with the largest deviation is rejected if it falls outside **Sigma Factor** times the standard deviation are rejected. The average is then taken of the remaining pixels.
SD Mask – a custom variation on Sigma Clip contributed by Ray Gralak. This is an iterative algorithm that more effectively removes outlier pixels while preserving "good" pixels. It is most useful when the number of images available is too small for effective use of Sigma Clip.
Drizzle – a method intended for combining undersampled, dithered images developed by Andy Fruchter (Space Telescope Science Institute) and Richard Hook (Space Telescope European Coordinating Facility). This process, formally called Variable-Pixel Linear Reconstruction, can restore detail finer than the pixel size of the frames being combined. The technique is described at http://xxx.lanl.gov/abs/astro-ph/9808087.

Image Combining Methods

There are a variety of means for combining subframes into a final exposure, and each has advantages:

- Mean or Average Combine
- Median Combine
- Sigma Clip Combine

Mean or Average Combine

This method provides the best SNR increase but is worst at removing non-random noise. If a non-random artifact (esp. hot and cold pixels) occurs on the same pixel in each image, they will not be removed by this method. Dithering is a good method for minimizing hot and cold pixel artifacts.

$$\mathrm{SNR} \propto \sqrt{N}$$

For example, for N=5, SNR is proportional to 2.2.

http://starizona.com/acb/ccd/advtheoryexp.aspx

Image Combining Methods-Median Combine

Median Combine

Median combine rejects the highest and lowest pixel values and thereby removes extremely bright semi-random artifacts such as cosmic rays. However, since hot and cold pixels remain the same from image to image, they are not removed by median combine unless dithering is used. Median combine is better at artifact removal but at the expense of reduced SNR in terms of random noise.

$$\mathrm{SNR} \propto \sqrt{\frac{2N}{\pi}}$$

For example, for N=5, SNR is proportional to 1.78, or only 81% that of the mean combine method.

http://starizona.com/acb/ccd/advtheoryexp.aspx

Image Combining Methods - Min/Max-Clip Combine

Min/Max-Clip Combine
MM-clip offers the best non-random noise reduction and can have less SNR loss than median combine. MM-clip rejects the highest or lowest value before taking a median value from the remaining pixel values. This eliminates extreme pixel values from contributing to the median value.

$$\mathrm{SNR} \propto \sqrt{N - 2}$$

For N=5, MM-clip SNR is proportional to 1.73, slightly less than that for median combine. But for N=6, MM-clip SNR is proportional to 2, whereas median SNR is proportional to 1.95. So for greater than 6 subframes, it is preferable to use the Sigma Clip combine routine. This argues for using a greater number of subframes. In fact, for greater than 11 subframes, MM-clip SNR loss is less than 10% compared to mean combining, but it has greater non-random noise reduction.

http://starizona.com/acb/ccd/advtheoryexp.aspx

Image Combining - Sigma Clip

Sigma Clip

Sigma clip is an image combining technique which reduces extreme pixel values by using data from surrounding pixels. While the end result is similar to using Min/Max-clip, the methods used to obtain the results are different. Due to the method used to determine the combined pixel values the effect on SNR is not predictable. However, the end result is often very similar to using MM-clip. MM-clip is available in the CCDStack and Mira software packages, while Sigma Clip is used in MaxIm DL. Either method is a good choice when combining a large number of subframes.

http://starizona.com/acb/ccd/advtheoryexp.aspx

Defining SNR with and without Stacking Summary

- Signal-to-Noise-ratio (SNR) equation was define that included effects of stacking

$$SNR = \sqrt{N}\,\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

SNR – Signal-to-Noise Ratio
N – number of subs of equal duration, equal temperature and binning
t – multiples of Sub duration, equivalent to minutes if sub duration is 1 minute
Starget – Target signal with sky background (Including DC and bias) removed
Ssky – Sky signal with DC (Including bias) removed
DC – Dark Current with Bias removed
Rnoise – Camera Read Noise

$$where \;\; S_{Target} = \text{Target} - Sky$$

$$S_{Sky} = Sky - Dark$$

$$DC = Dark - Bias$$

- Analysis was provided to Verify that noise is the square root of the signal

Defining SNR with and without Stacking

Summary (continued)

- Image Combine Methods consist of two distinct parts: Rejection and combination
  - The goal of a pixel rejection algorithm is to exclude outliers from the set of pixels that are to be combined in each pixel stack.
  - Combination or the image integration process combines the components of each pixel stack into one pixel of an *integrated image*. There are different methods to improve the signal-to-noise ratio (SNR) using different pixel combination operations.
- There are a variety of means for combining subframes into a final exposure, and each has advantages: The following were discussed.
  - Mean or Average Combine
  - Median Combine
  - Sigma Clip Combine

Agenda

- Astro-Photography Definitions with some examples
- Capturing Faint Detail with Astrophotography
  - Signal-to-Noise (SNR) Intro
  - Methods of Improving SNR
    - Calibration and Stacking
    - The Darker the Skies, the better the Image
  - Defining SNR with and without Stacking
  - Estimating Exposure Times and Number of Subs
  - Image Capture Strategies
    - SNR
    - Resolution
- Summary
- Conclusions

Estimating Exposure Times and Number of Subs

As a minimum, Astro-Imagers are concerned about 4 things after choosing an image to photograph:

1. Exposure Time (t or T_{Exp})
2. Number of Subs (N)
3. Total exposure time ($T_{TotalExp}$)
4. Signal-to-noise ratio (SNR)

SNR equation
(from previous)

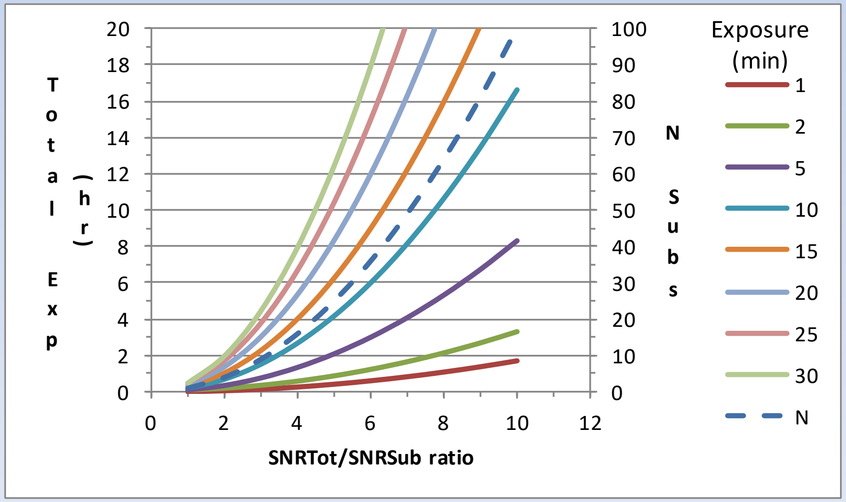
$$SNR = \sqrt{N}\,\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

Ancillary
equations

$$SNR_T = \sqrt{N} * SNR \qquad where \quad N = \frac{T_{TotalExp}}{T_{Exp}}$$

$$\frac{T_{TotalExp}}{T_{Exp}} = \left(\frac{SNR_T}{SNR}\right)^2 \qquad T_{Exp} = \frac{T_{TotalExp}}{\left(\frac{SNR_T}{SNR}\right)^2}$$

$$T_{TotalExp} = T_{Exp}\left(\frac{SNR_T}{SNR}\right)^2 \qquad N = \left(\frac{SNR_T}{SNR}\right)^2$$



Estimating Exposure Times and Number of Subs (continued)

Compute % SNR per number of subs

From previous page;

$$SNR_{TOT} = \sqrt{N}\ SNR_O$$

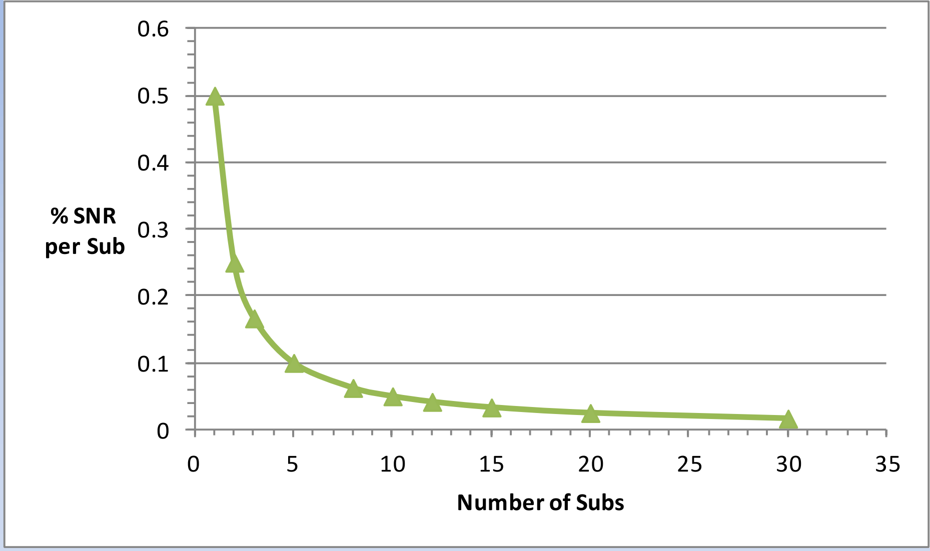
- SNR equation

$$S\dot{N}R_{TOT} = \frac{SNR_O}{2\sqrt{N}}$$

- SNR rate

$$\%\Delta SNR_{TOT} = \frac{\frac{SNR_O}{2\sqrt{N}}}{\sqrt{N}\ SNR_O} = \frac{1}{2N}$$

- SNR rate/SNR equation



Graphing the final equation from above, it is seen that the SNR change per sub reduces as the number of subs increases. This demonstrates that adding subs to increase SNR has diminishing returns

Example: 10% change in SNR = 5 subs
5.0% change in SNR = 10 subs
2.5% change in SNR = 20 subs

Note: curve is valid for any exposure time, read/DC noise or object/background SNR

Estimating Exposure Times and Number of Subs (continued)

Compute % SNR per exposure time for one sub

$$SNR = \frac{t\,S_{Target}}{\sqrt{t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}}}$$

- SNR equation

$$S\dot{N}R = \frac{S_{Target}}{\sqrt{t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}}} - \frac{0.5\,t\,S_{Target}\left(S_{Target} + S_{Sky} + DC\right)}{\sqrt{\left(t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}\right)^{3}}}$$

- SNR rate

$$\%\,\Delta\,SNR = \frac{\dfrac{S_{Target}}{\sqrt{t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}}} - \dfrac{0.5\,t\,S_{Target}\left(S_{Target} + S_{Sky} + DC\right)}{\sqrt{\left(t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}\right)^{3}}}}{\dfrac{t\,S_{Target}}{\sqrt{t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}}}}$$

- SNR rate/SNR equation

$$\%\,\Delta\,SNR = \frac{1}{t} - \frac{0.5\,t\,S_{Target}\left(S_{Target} + S_{Sky} + DC\right)}{t\,S_{Target}\left(t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}\right)}$$

- Simplify

$$\%\,\Delta\,SNR = \frac{1}{t} - \frac{0.5\,\left(S_{Target} + S_{Sky} + DC\right)}{t\,\left(S_{Target} + S_{Sky} + DC\right) + R^{2}_{Noise}}$$

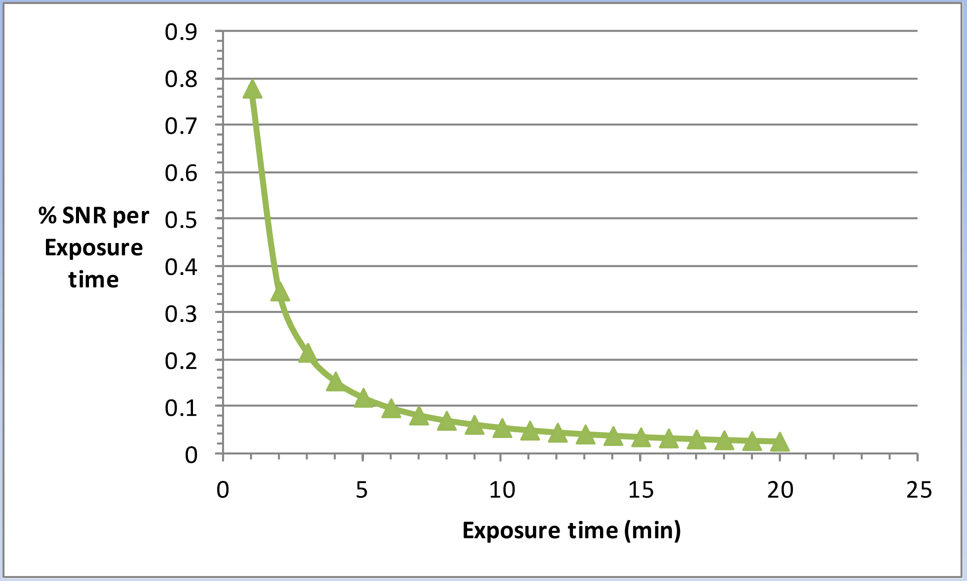
- Final

Estimating Exposure Times and Number of Subs (continued)

Compute % SNR per exposure time for one sub (continued)

$$\% \, \Delta \, SNR = \frac{1}{t} - \frac{0.5 \, (S_{Target} + S_{Sky} + DC)}{t \, (S_{Target} + S_{Sky} + DC) + R^2_{Noise}}$$

Graphing the final equation shows that increasing exposure time to increase SNR has diminishing returns. Trend is same as shown with number of subs.



Example: 11 min = 5% change in SNR
21 min = 2.5%

Note: curve is valid for any exposure time for given object/sky signal, and read and DC noise

	e-/min
Starget	27.45
Ssky	40.22
DC	0.222
Rnoise	9.3

Values obtained from a M74 image sub. Target signal from a dim portion of M74

Estimating Exposure Times and Number of Subs (continued)

Compute % SNR per exposure time for one sub (continued)

Solving for exposure time for a specified Rnoise, % SNR Change and the Total Signal (S_{Target} + S_{sky}+ DC), the following parameter sensitivities are determined

$$t = \frac{\frac{-\left(SNR_{\%}\, R_{Noise}^{2} - 0.5 * \left(S_{Target} + S_{Sky} + DC\right)\right)}{SNR_{\%} * \left(S_{Target} + S_{Sky} + DC\right)} + \sqrt{\left(\frac{\left(SNR_{\%}\, R_{Noise}^{2} - 0.5 * \left(S_{Target} + S_{Sky} + DC\right)\right)}{SNR_{\%} * \left(S_{Target} + S_{Sky} + DC\right)}\right)^{2} - \frac{4 * R_{Noise}^{2}}{SNR_{\%} * \left(S_{Target} + S_{Sky} + DC\right)}}}{2}$$

		Rnoise = 4 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	10	6.0	11.2	21.4
	20	5.6	10.7	20.7
	40	5.3	10.4	20.4
	67.892	5.2	10.2	20.2
	80	5.2	10.2	20.2
	160	5.1	10.1	20.1
	320	5.0	10.0	20.0
	640	5.0	10.0	20.0
	1280	5.0	10.0	20.0

		Rnoise = 9.3 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	10	7.7	13.8	25.1
	20	6.9	12.6	23.1
	40	6.3	11.6	21.8
	67.892	5.9	11.0	21.1
	80	5.8	10.9	21.0
	160	5.5	10.5	20.5
	320	5.2	10.3	20.3
	640	5.1	10.1	20.1
	1280	5.1	10.1	20.1

		Rnoise = 18 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	10	8.9	16.6	30.3
	20	8.3	15.2	27.4
	40	7.6	13.7	24.9
	67.892	7.0	12.7	23.4
	80	6.9	12.5	23.0
	160	6.2	11.5	21.7
	320	5.7	10.9	20.9
	640	5.4	10.5	20.5
	1280	5.2	10.2	20.2

		Rnoise = 36 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	10	9.7	18.7	35.7
	20	9.4	17.8	33.2
	40	8.9	16.6	30.3
	67.892	8.5	15.5	28.1
	80	8.3	15.2	27.4
	160	7.6	13.7	24.9
	320	6.9	12.5	23.0
	640	6.2	11.5	21.7
	1280	5.7	10.9	20.9

- As expected, as Read noise increases, the exposure time has to increase to reach the same level of SNR diminishing returns
- As the total signal increases, the exposure time reduces as the Read noise is over whelmed earlier to achieve the SNR diminishing returns value.

Note: % SNR Change is shown in decimal format

Estimating Exposure Times and Number of Subs (continued)

Compute % SNR per exposure time for one sub (continued)

- Another note from the sensitivity data, as the signal (Target+Sky+DC) decreases, the exposure time must be increased to over whelm the read noise.
  - Use a camera with low read noise in a dark sky when shooting dim objects to minimize exposure time
- The previous results also indicated that for a specified level of % SNR change, the exposure time approached a constant value as Read noise decreased and the total signal increased.
  - This effect is apparent when looking at the equation

$$\%\,\Delta\,SNR = \frac{1}{t} - \frac{0.5\,t\,S_{Target}\left(S_{Target} + S_{Sky} + DC\right)}{t\,S_{Target}\left(t\left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}\right)}$$

  - When Rnoise = 0, then the above equation reduces to 0.5/t or

10.0% change in SNR = 5 min
5.0% change in SNR = 10 min
2.5% change in SNR = 20 min

Estimating Exposure Times and Number of Subs (continued)

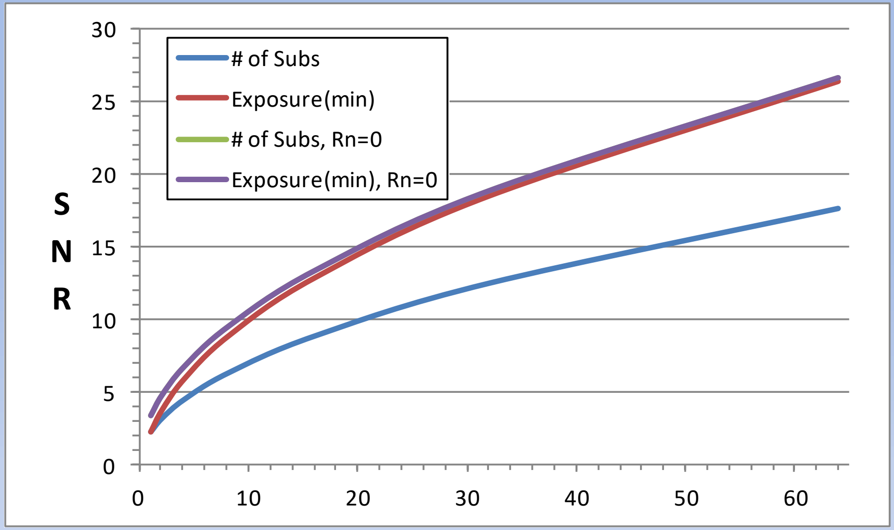
Compute % SNR per exposure time for one sub (Continued)

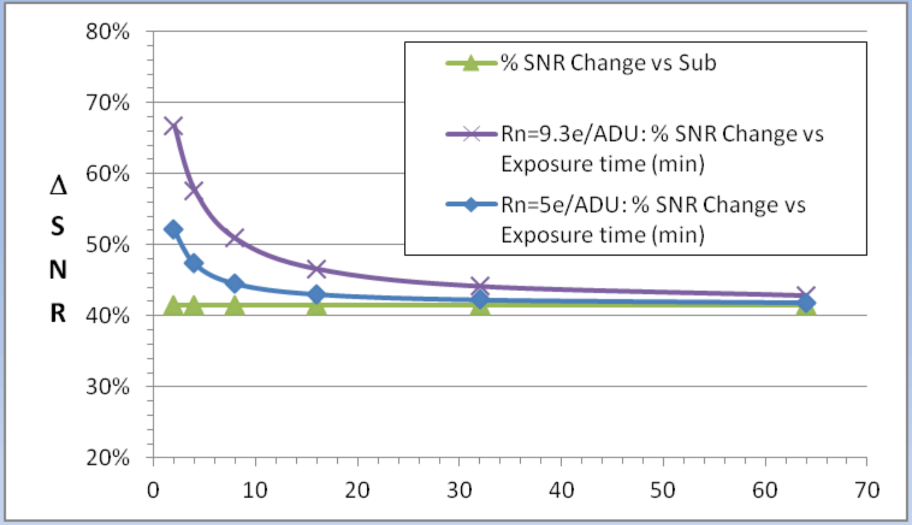
- This is exactly the relationship that was found with number of subs
  - This can be seen after rewriting the SNR equation with Rnoise=0

$$SNR = \sqrt{N}\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right)}} = \sqrt{N}\sqrt{t}\frac{S_{Target}}{\sqrt{\left(S_{Target} + S_{Sky} + DC\right)}}$$

  - Therefore, the effect on SNR whether doubling the number of subs or the exposure time is exactly the same if Read noise =0.
  - Question: **Which is preferred, adding subs or increasing exposure time to increase SNR the fastest?**

SNR increases Faster by increasing Exposure time vs adding Subs when Read Noise is Present





- This may sound counter intuitive as the presence of Read noise reduces SNR.
  - As exposure time increases, the read noise effect on SNR approaches 0, and SNR approaches the no read noise curve (purple curve: left chart). Increasing the number of subs does not reduce effect of read noise, so SNR does not approach the no read noise curve, but continues to increase at the rate of $N^{1/2}$ from the reduced starting SNR.
  - Therefore, exposure time will always outperform number of subs in total SNR (see red curve and blue curve in left chart).

Note: exposure time has a maximum value depending on equipment or whether the sub exposure time is being limited to maximize sub keep percentage. After that point SNR can only be increased by adding subs

Estimating Exposure Times and Number of Subs (continued)

- Example of how to use previous discussion to determine number of subs and exposure time based on SNR.
  - Let's assume that 5% SNR diminishing return is desired.
  - From the previous data, assuming a read noise of 9.3e- and M74 data
    - Number of subs would be 10 subs
    - Exposure time would be 11 min
    - Total exposure time = 110min
  - However, since number of subs and exposure time are both at 5% SNR diminishing return, the result is really a total of 10% SNR diminishing return. So to really obtain a 5% SNR diminishing return, both number of subs and exposure time should be at 2.5%.
    - Number of subs would be 20 subs
    - Exposure time would be 21 min
    - Total exposure time = 420min
  - If considering shooting LRGB that would be
    - 440 min (7.3 hrs) for 10% SNR diminishing returns
    - 1680 min (28 hrs) for 5% SNR diminishing returns

Estimating Exposure Times and Number of Subs (continued)

- Choosing to obtain a 2.5% SNR diminishing returns would be a sizable time commitment per LRGB image
- So backing down to a 5% value would reduce the time commitment by almost a factor of 4, but may be hard to accept not increasing SNR by 10% with only adding one more minute and one more sub.
  - So the real answer may be somewhere in between.
- Before finalizing the choice of an exposure time and number of subs lets look at some other constraints that should be considered.

1) Sub keep percentage
2) Noise reduction with image stacking
3) Image saturation
4) Image Combination
5) Uniform background

Estimating Exposure Times and Number of Subs (continued)

1) **Sub keep percentage**
    - The set of **equipment** that is being used will limit the exposure time by maximizing the time that will prevent unacceptable image smear.
        - Causes: mount type and fidelity, polar alignment, guiding method, telescope/camera focal length
            - **mount type** – alt-azimuth mount will limit exposure time due to image field rotation. Equatorial mount is better.
            - **mount fidelity** – poorly constructed or light weight can cause vibration. Poor fidelity motors in the mount can cause tracking errors.
            - **polar alignment** – Errors in polar alignment for an equatorial mount or star align errors for an alt-azimuth mount will limit maximum exposure time
            - **guiding method** – fixed on tripod, open loop manual or auto tracking have maximum exposure time limits. auto guiding does not have any limits, but is susceptible to atmosphere instabilities, mount tracking errors and telescope/camera focal length.

Estimating Exposure Times and Number of Subs (continued)

1) **Sub keep percentage (continued)**
        - **telescope/camera focal length** – longer the telescope/camera focal length, the better the performance of all the previous items must be.
    - **Uncontrolled events**: meteors, airplanes, satellites, wind, lights all can spoil an a sub. The longer the exposure the higher the risk in having to throw away a sub.

Therefore the equipment being used, your time commitment and patience will limit the maximum exposure time that is acceptable (Sub-keep percentage)

Estimating Exposure Times and Number of Subs (continued)

2) Noise estimate reduction with image stacking

- As mentioned early in this document, stacking multiple images reduces the noise estimate in the image by $1/N^{1/2}$
  - The example was 100 subs reduces noise to 10%
  - The important message here is that every time the number of subs are doubled the noise is reduced by 0.707.
  - 1 sub = 1.0
  - 2 subs = 0.707
  - 4 subs = 0.5
  - 8 subs = 0.35
  - 16 subs = 0.25
  - 32 subs = 0.18
  - 64 subs =0.12
  - 128 subs= 0.09

Estimating Exposure Times and Number of Subs (continued)

3) Image Saturation

- The longer the exposure and the more subs that are used, the objects in the image may become saturated or turn white. When this happens additional images may need to be taken at a shorter exposure time and then used to replace the saturation regions during processing. If this happens with stars, image processing can be used to make less noticeable in the final image.

- Estimate of when this occurs is knowing the Full-well depth of the camera (see Full-well depth definition), the camera gain and the number of photons collected during a sub.
  - Example: a 16 bit camera can handle 2^16 = 65536 ADU. Multiplying by the camera gain gives the number of photons that can be collected before saturation or clipping. If the gain is 0.37 than 24248 photons can be collected before saturation. If a star or parts of the image is collected at 243e- per min than saturation would occur at approximately 100 minutes.

Estimating Exposure Times and Number of Subs (continued)

4) Image Combination

- This was discussed previously, but not from a point of view of number of subs

- From before; Image Combination consist of two distinct parts: Rejection and combination.

  - Notice that the PixInsight rejection algorithms have a minimum number of subs requirement. Therefore if PixInsight is used, this needs to be considered in determining the number of subs to be used in imaging a subject.
  - Maxim DL does not seem to specify the minimum number of subs in their documentation, but probably it is more than 1.

Estimating Exposure Times and Number of Subs (continued)

5) Uniform background

- When an image is captured, the image contains the signals from the desired image and from unwanted signals, such as the sky background and stray light. When the image is processed, the sky background and camera produced backgrounds are subtracted to leave only the wanted signal from the sky object. The resulting image then provides the beautiful, low noise deep sky image that is desired.

- When the backgrounds are subtracted, it is assumed that the backgrounds are known very well. But is that really true for all durations of image sub, dark and bias.

  - Photons striking the camera focal plane follow a Poisson distribution. The standard deviation of the number of photons striking the focal plane starts at a very high value and as the exposure duration increases the standard deviation starts to approach a finite lower value. Another way to think about it is the mean value of the signal approaches the correct value. This is demonstrated on the “**Verification that noise is square root of signal”** previous chart.

  - Note that the dark and bias calibration is included. Since during image calibration they are also being subtracted from the images, they too should have an uniform background. Therefore, the number of subs of the darks and Bias frames will affect the calculation of the average or median noise.

Sky Background Limited (continued)

5) Uniform background (continued)

- In the discussion of noise in the SNR section, it was shown that the camera read noise dominates early in the exposure until the signal gets high enough to swamp the read noise effect.

- So the solution, is to expose for a long enough duration that the sky noise dominates all fixed noise sources. Then by the use of image stacking, the random noise in individual pixels can be reduced resulting in a smoother sky background that can be subtracted or processed. Depending on the camera, Read Noise and/or Dark Noise usually will be the dominate random noise early in the exposure.

- With this knowledge and the SNR equation previously defined, the exposure time can be determined when the sky noise dominates the read and/or dark noise.

Sky Background Limited (continued)

5) Uniform background (continued)

- The derivation to determine the minimum exposure time to create an uniform background was popularized by John C. Smith. The original derivation is included for reference with the discussion of exposure calculators that occurs in a few charts. The following version is a more general version.

$$\frac{\sqrt{t(S+DC)+\ R_{Noise}^{2}}}{\sqrt{t(S)}} = (1+P)$$

$$\sqrt{t(S+DC)+\ R_{Noise}^{2}} = (1+P)\sqrt{t(S)}$$

$$t(S+DC)+\ R_{Noise}^{2} = (1+P)^{2}\ t(S)$$

$$t(S+DC)+\ R_{Noise}^{2} = (1+P)^{2}\ t(S)\ =\ t(S)+\ 2P\ t(S)+P^{2}\ t(S)$$

$$R_{Noise}^{2} = t(-S+S+\ 2P\,S+P^{2}\ S-DC) = t(2P\,S+P^{2}\ S-DC)$$

$$R_{Noise}^{2} = -t(S)-tDC+t(S)+\ 2P\ t(S)+P^{2}\ t(S)$$

$$t = \frac{R_{Noise}^{2}}{S\ (2P\ +P^{2}\ )-DC} = \frac{R_{Noise}^{2}}{S\ P\ (2\ +P\ )-DC}$$

S = Signal (can be S_{target}, S_{sky} or both)
P = percent of total noise that read noise should be in decimal (for example 5% = 0.05)

Sky Background Limited (continued)

5) Uniform background (continued)

- For uniform Sky background $t = \dfrac{R^2_{Noise}}{S\,P\,(2+P) - DC}$
  - Using Ssky background value provided below, a Rnoise=9.3 and %Rnoise of signal =5% , t = 22.2 min

		Rnoise = 4 (e-)		
		% Rnoise of Signal		
		0.1	0.05	0.025
Signal (e-/min)	10	8.5	19.9	56.3
	15	5.5	12.2	29.8
	20	4.0	8.8	20.2
	27.45	2.9	6.2	13.7
	40.22	1.9	4.1	8.8
	67.67	1.1	2.4	5.0
	80	1.0	2.0	4.2
	160	0.5	1.0	2.0
	320	0.2	0.5	1.0

		Rnoise = 9.3 (e-)		
		% Rnoise of Signal		
		0.1	0.05	0.025
Signal (e-/min)	10	46.1	107.7	304.3
	15	29.5	65.7	160.9
	20	21.7	47.3	109.4
	27.45	15.6	33.4	74.1
	40.22	10.5	22.2	47.7
	67.67	6.2	12.9	27.0
	80	5.2	10.8	22.6
	160	2.6	5.3	11.0
	320	1.3	2.7	5.4

- Notice: at large signals, the t to reach an uniform background reduces, but does get very large as Rnoise increases.

		Rnoise = 18 (e-)		
		% Rnoise of Signal		
		0.1	0.05	0.025
Signal (e-/min)	10	172.5	403.5	1139.8
	15	110.7	246.3	602.9
	20	81.4	177.2	409.9
	27.45	58.5	125.0	277.5
	40.22	39.4	83.1	178.6
	67.67	23.2	48.3	101.1
	80	19.5	40.6	84.6
	160	9.7	20.0	41.1
	320	4.8	9.9	20.3

		Rnoise = 36 (e-)		
		% Rnoise of Signal		
		0.1	0.05	0.025
Signal (e-/min)	10	690.1	1613.9	4559.4
	15	442.6	985.2	2411.7
	20	325.8	709.0	1639.5
	27.45	233.8	500.1	1109.9
	40.22	157.6	332.3	714.4
	67.67	92.6	193.0	404.5
	80	78.2	162.4	338.6
	160	38.8	80.1	164.5
	320	19.3	39.8	81.1

	e-/min
Starget	27.45
Ssky	40.22
DC	0.222
Rnoise	9.3

Values obtained from a M74 image sub. Target signal from a dim portion of M74

S = Signal (can be S_{target}, S_{sky} or both)
P = percent of total noise that read noise should be in decimal (for example 5% = 0.05)

Sky Background Limited (continued)

5) Uniform background (continued)

Summary

- Read noise and DC noise dominates the signal until enough photons from a target is collected. These photons consist of the target of interest, sky background (including stray light), and signals generate by the camera's electronics. It is desired to have good images before image stacking begins. Each image should have enough exposure to generate good mean values with small statistical deviation of the signal on each pixel. This is a statistical game, get enough photons from the target of interest over time that overwhelm the photons from the unwanted signal sources. So when the background is subtracted from the image only the target of interest signal remains. This is difficult to do as usually the target of interest signal is only slightly higher than the background. This requires as uniform of background as can be collected, and so the discussion of "Sky Background Limited" exposures.

- Data indicated that as signal decreased, the exposure time to achieve a read noise of say, 5% increased. The exposure time reduced as Read noise reduced. This should be apparent and consistent with the last few charts. Although it may have been more apparent that a conclusion was that high background signals was preferred as it provided shorter exposure times. Although this is true, a better take away would be that with high background signals the read noise is over whelm with shorter exposures, but at the expense of great image. Longer exposures is just collecting more unwanted signal.

Sky Background Limited (continued)

5) Uniform background (continued)

Summary(continued)

- Notice that the total signal (target+sky) for a read noise of 9.3 and 5% requires only 12.9 min to over whelm the read noise. The sky background makes up the majority of the signal requires 22.2 min. And the target with the lowest signal requires 33.4 min.

- If the background was not to be removed from the image the exposure time would be 12.9 min. But the background needs to be removed and an uniform background is needed, so the exposure time needs to be 22.2min to over whelm the read noise. The target of interest time of 33.4 min is not considered because the total signal and background has overwhelmed the read noise, the subtraction of the background from the total signal has essentially overwhelmed the majority of the read noise with the 5% still remaining.

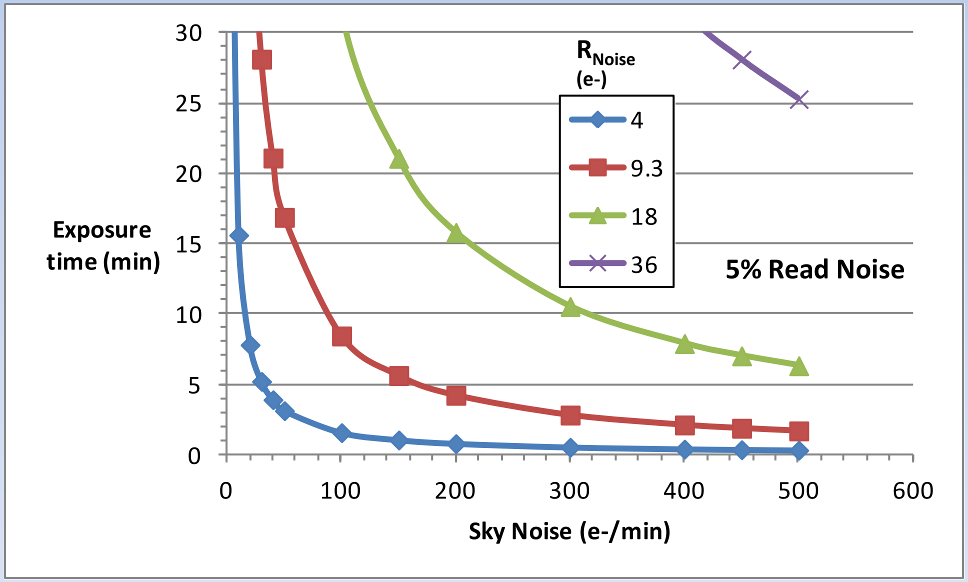
- From the data chart, it should be apparent that as the background becomes better by having a darker sky, exposure time to over whelm read noise increases dramatically. So what can be done about it?
    1) Reduce read noise by getting a better camera more suited to the darker sky
    2) Increase aperture and/or shorter focal length
    3) Improve mount and tracking equipment to allow longer exposures
    4) Accept lower sub keep percentage which will sometimes require reshooting the sub.
    5) Accept that Read noise may have a higher percentage of the signal than desired

Sky Background Limited (continued)

5) Uniform background (continued)

Summary (continued)

- The main issue with using the uniform sky background is in a dark sky setting. The exposures needed may be longer than equipment, sub keep percentage or patience will allow. The graph provides a visually of how the uniform sky background levels affects the exposure time. Compare to your equipment limits and seeing to determine how it effects you.



The conclusion is that in deciding the exposure length, many compromises have to be made between the performance achieved versus budget, the amount of processing and patience. This will be seen through this package.

Exposure Calculators

Exposure Calculators are used to get an quick estimate of the total exposure time, number of subs and sub duration for a particular image.

There are several available, the following is an incomplete list.

- **John C. Smith Calculator**
- **PixInsight (PI) CalculateSkyLimitedExposure Script**
- **Maxim DL Add-on ExposurePlanning Script**

Sky Limited Exposures by John C. Smith

$$t_{ORN} = \frac{9.76R_{on}^{2}}{E_{sky}}$$

The trick now is to determine E_{sky}, the sky background flux. By measuring the background ADU value from a test image, as shown in the examples above, the sky background flux can be calculated from the following equation:

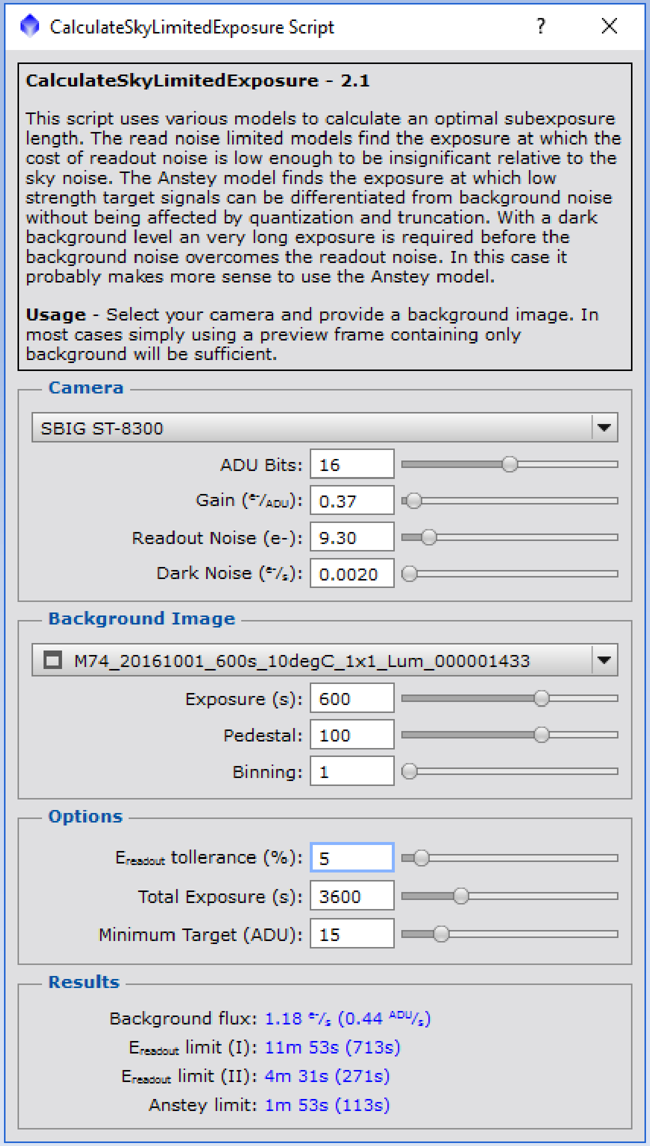
$$E_{sky} = \frac{(ADU_{bkg} - 100)g}{t_{test}}$$

Here ADU_{bkg} is the background ADU count, g is the gain, t_{test} is the test exposure duration in minutes. Take the first example given earlier, of the image taken from the dark location. The ADU_{bkg} value was determined to be 950. 100 is subtracted for the pedestal value described above. The gain of the ST-10XME camera used is 1.3e- and the exposure was 10 minutes. This gives a value of E_{sky} = 111e-/min (equal to the 1.8 e-/sec from the example).

This value of E_{sky} is then plugged into the t_{ORN} equations. The readout noise for the ST-10XME is 7e-. For a 5% contribution from readout noise, the necessary exposure is 4.3 minutes. This implies that the 10 minute exposure was well beyond that needed to overwhelm the readout noise from the camera and is a sky limited exposure.

http://starizona.com/acb/ccd/advtheoryexp.aspx

PixInsight Script for Calculating Exposures



CalculateSkyLimitedExposure Script

CalculateSkyLimitedExposure - 2.1

This script uses various models to calculate an optimal subexposure length. The read noise limited models find the exposure at which the cost of readout noise is low enough to be insignificant relative to the sky noise. The Anstey model finds the exposure at which low strength target signals can be differentiated from background noise without being affected by quantization and truncation. With a dark background level an very long exposure is required before the background noise overcomes the readout noise. In this case it probably makes more sense to use the Anstey model.

Usage - Select your camera and provide a background image. In most cases simply using a preview frame containing only background will be sufficient.

Camera

SBIG ST-8300

ADU Bits: 16

Gain ($^{e-}/_{ADU}$): 0.37

Readout Noise (e-): 9.30

Dark Noise ($^{e-}/_{s}$): 0.0020

Background Image

M74_20161001_600s_10degC_1x1_Lum_000001433

Exposure (s): 600

Pedestal: 100

Binning: 1

Options

$E_{readout}$ tollerance (%): 5

Total Exposure (s): 3600

Minimum Target (ADU): 15

Results

Background flux: 1.18 $^{e-}/_{s}$ (0.44 $^{ADU}/_{s}$)

$E_{readout}$ limit (I): 11m 53s (713s)

$E_{readout}$ limit (II): 4m 31s (271s)

Anstey limit: 1m 53s (113s)

Exposure Planner

Exposure Planner is a plug-in for MaxIm DL that allows you to inspect an area of an image and determine how many exposures you will need to reduce the noise to an acceptable level.

To install this plug-in, you have to run the program "Install Exposure Planner V1.2.exe", which will copy the necessary files to your disk. Then you must also run MaxIm DL and use its "Add Plug-in" command to make the plug-in available. By default the plug-in is installed in Window's "program files" area.

> Warning: depending on which version of MaxIm DL you have, you may need to run it as administrator while you are installing Exposure Planner. Once the installation is complete, you can go back to running MaxIm DL as an ordinary user.

To use the plug-in, use MaxIm DL to take a single trial image of your target using the exposure time you intend to use when you start your session. For more accurate results, you can take several images and stack them. But be careful to have this be an average of the images, not the sum. However, one exposure is probably sufficient for most cases. The exposure(s) should be calibrated to remove dark and flat field problems.

Then drag your mouse over a part of the image that you would like to study. Exposure Planner will give you a prediction of how many exposures to take and how long your session time will be.

To get a copy of Exposure Planner, click here .

Last modified on December 10, 2013

http://www.darklights.org/simccd/planner.shtml

Exposure Planner

Exposure Planner V1.2

Pick a camera from the drop down list or enter the Gain and Readout noise for your camera. Then select an area you want to study and set the" Desired Signal to Noise Ratio" to the amount of noise you are willing to tolerate in that area. The utility will tell you how many pictures to take and how long it will take to do that. If the sky brightness seems wrong, select the darkest part of the image and press the "Set Sky" button.

Camera: SBIG ST-10XME
Gain: 1.375
Readout Noise: 10.58
Desired SNR: 10
Frame Time: 300

Signal = 10.31
Frame count = 1060
Total time (hh:mm) = 88:20

Learn about the companion application SimCCD at www.darklights.org/simccd.

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hdjones@pacbell.net

Figure 43 The Exposure Planner's window

http://www.darklights.org/simccd/planner.shtml

Estimating Exposure Times and Number of Subs (continued)

Summary

- Hopefully with the previous discussion this summary should be obvious.
- There are a series of constraints on defining the exposure time and number of subs in capturing an image.

1. Equipment capability to produce long exposure times (budget)
2. Patience & time, including sub keep percentage and diminishing returns
3. Signal rejection and combination
4. Uniform Background
5. SNR
6. Noise reduction by stacking
7. Image saturation

Assumed signals

target 27e-/min, background 40 e-/min and DC noise of 0.2 e-/min

Based on 5% SNR diminishing returns for the combination of subs and exposure time; 20 subs and 21 min exposure time. Based on a read noise of 9.3e-, 5% Read noise contribution and background of 40e-/min, the uniform background exposure was about 22 min. Noise reduction by stacking suggested 16 subs or greater. Signal rejection and combination allowed many options but best was a rejection algorithm that required 15 or more subs.

Estimating Exposure Times and Number of Subs (continued)

Summary

At a first cut all the constraints have created a narrow selections of exposure times and number of subs.

- 16-20 subs and 22 min exposure which creates a total exposure time of 352-440min or 5.9hrs -7.3hrs per filter.

- Assuming shooting LRGB that makes the total exposure time of 23.6-29.2 hrs per subject

That will task the patience and available time!!!

So what can be done to reduce this time?

Actually nothing unless willing to compromise on the performance or your budget!

One thing that could be done is choose a 10% diminishing return on SNR and accept a higher read noise percentage, that would reduce the time allotment by about 50%.
OR
Choose another rejection algorithm that reduces number of subs to 6-8 and accept higher noise/outliers would also reduce the time allotment by about 50%

Now we are getting somewhere on reducing total exposure time!

Is there anything else that can be done?
Yes, and that leads into the next section.

Agenda

- Astro-Photography Definitions with some examples
- Capturing Faint Detail with Astrophotography
  - Signal-to-Noise (SNR) Intro
  - Methods of Improving SNR
    - Calibration and Stacking
    - The Darker the Skies, the better the Image
  - Defining SNR with and without Stacking
  - Estimating Exposure Times and Number of Subs
  - Image Capture Strategies
    - SNR
    - Resolution
- Summary
- Conclusions

Image Capture Strategies

Image capture strategies which includes **Binning** is probably one of the top controversially topic of astro-Imagers. An image capture strategy is the exposure time, number of subs and BIN of each filter used to create a LRGB image. Generally, an image capture strategy is selected to reduce total exposure time and at the same time minimize SNR performance loss. This rationale is when "Binning" come in to play.

If you ask an astro-imager why they "Bin", the number one answer will probably be to reduce total exposure time. But is this really true?

Well the correct answer is…..it depends on your image capture strategy.

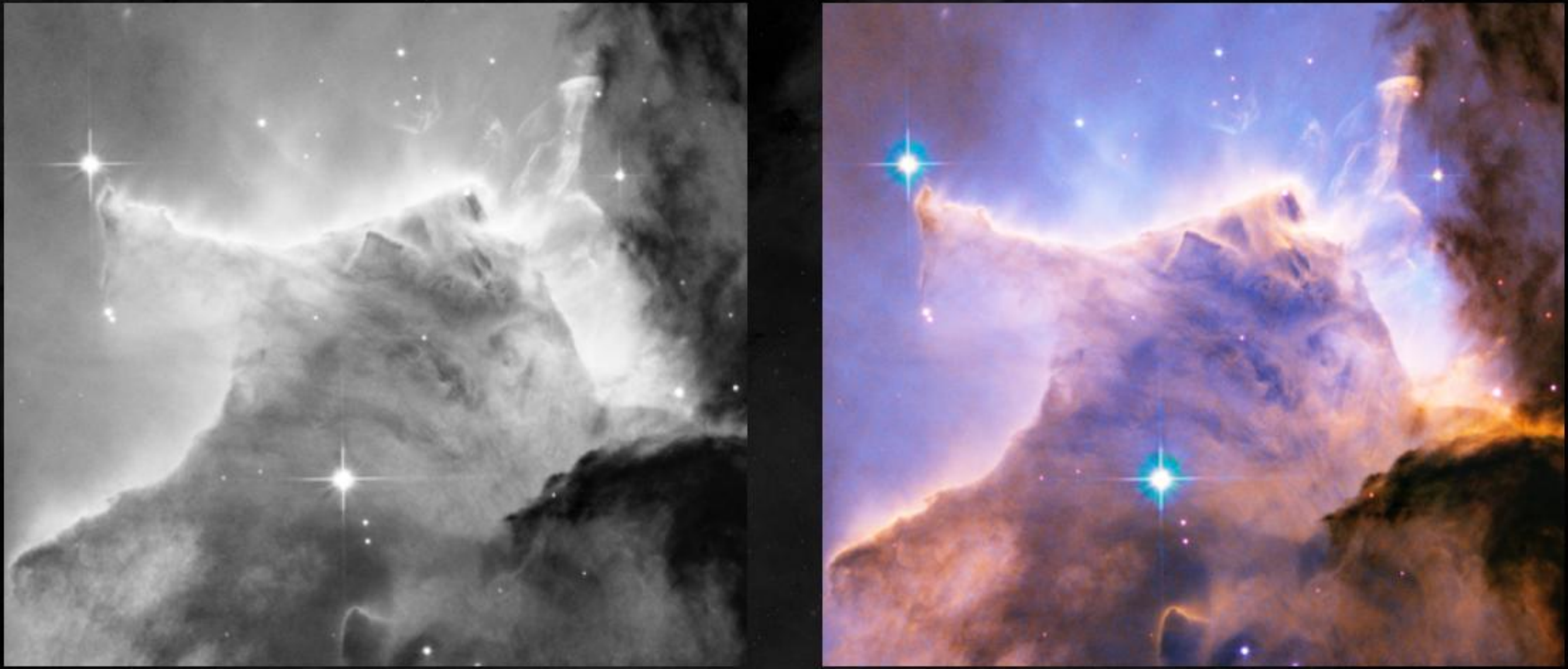
For example, let's say you image an object using the same exposure time for Luminance and each of the RGB channels but do not bin . Then repeat with 2x2 binning in each of the RGB channels. What is the difference in total exposure time? Hopefully, you say none, the total exposure would be the same, whether or not binning was performed.

Ok, now you would say, well we "really" bin because we want to increase the RGB SNR over not binning of RGB channels. And in doing so, we would save total exposure time over not binning. You may be surprised that this is only partially true.

We will start with the assertion of the following chart (and the controversy begins).

LRGB vs. RGB

- We are very perceptive of changes in Luminance across the image and less so of changes in Chrominance.
- We can (and should) sacrifice SNR of Chrominance to boost SNR of Luminance.



http://www.stark-labs.com

Image Capture Strategies (continued)

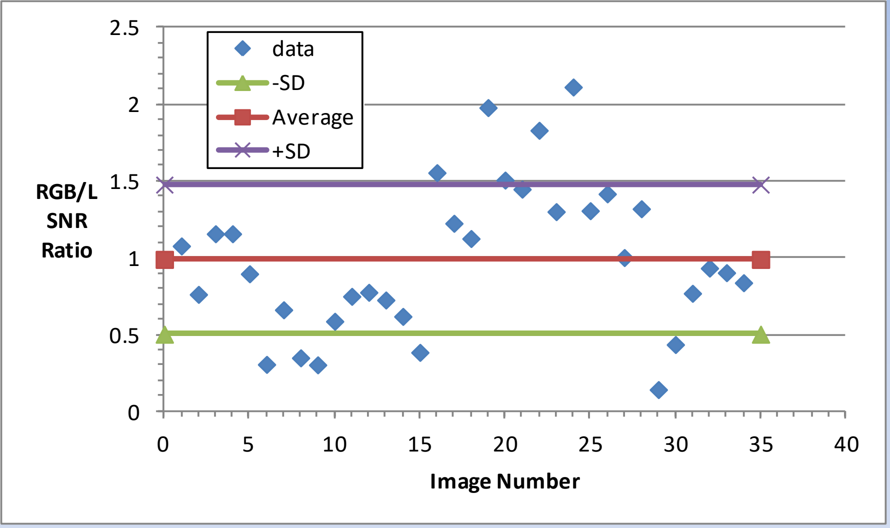
Things to consider in selecting an LRGB Image Capture Strategy

- Professional astronomers very seldom use color, except to highlight particular information related to their research
- To obtain the brightest color, only RGB should be shot. Adding Luminance will always subdue RGB. But Luminance adds detail. So there is a balance between RGB SNR and Luminance SNR that produces the most detail and acceptable color .
    - Getting more detail is the reason the LRGB is used so frequently.
- A combined R,G,B image will have more noise than a Luminance image
- Available Equipment
    - Use of DSLR or one shot color camera limits the available Image Capture Strategies to one, however, image processing does allow the creation and use of a synthetic Luminance obtained from the RGB image.
- Image SNR increases by the square-root of the number of subs
    - So every time you double the number of subs the SNR increases by the square-root of 2 or 1.414
- Image noise drops by 1 over the square root of the number of stacking subs
    - So every time you double the number of subs the noise drops by one over the square-root of 2 or 1/1.414. =0.707
    - 1 sub(1x), 2 subs(0.71x), 4subs(0.5x) , 8(0.35x) subs, 16(0.25x) subs, 32 subs(0.18x), 64 subs(0.13x)
- Max individual sub exposure time is limited by the sub keep percentage that you are willing accept from your equipment
    - Increasing Sub SNR beyond this limit requires increasing subs

Image Capture Strategies (continued)

What are Imagers using for their Image Capture Strategies?

The chart below depicts the RGB/L SNR ratio used from 10 imagers (27 images) taken a random. The average and standard deviation is also shown.



- A small survey of imagers as to the image capture strategies being used revealed a large variation from RGB/L SNR ratios from 0.14 to 2.0.
  - Average = 0.99, Standard Deviation = 0.49

The ratio RGB/L SNR ratio was selected as a reference because 1) it will be used later in additional analysis , 2) BIN 1 RGB & L SNR are approximately equal for constant exposure and number of subs, making RGB/L SNR ratio=1 making it a good reference point, 3) Binning is automatically included, 4) using the RGB/L SNR ratio makes SNR independent of true image signal so the ratio can be estimated based on exposure and number of subs and a reference signal with camera noise.

Data from taken SBIG yahoo user group and websites (LRGB only)

Image Capture Strategies (continued)

Small Sample of Image Capture Strategies used by Imagers

Imager	Object	L BIN	L Exp (min)	L subs	RGB BIN	RGB exp (min)	RGB Subs	LSNR	RGB SNR	RGB/L SNR Ratio	total exp	total exp ratio
Imager #1	stock 3	1	10	12	2	5	8	50.32	54.22	1.08	240	0.375
	M71	1	10	24	2	5	8	71.17	54.22	0.76	360	0.563
	NGC2683	1	10	18	2	10	6	61.63	71.30	1.16	360	0.563
	NGC3079	1	10	12	2	10	4	50.32	58.21	1.16	240	0.375
	NGC4147	1	10	40	2	10	8	91.87	82.33	0.90	640	1.000
Imager #2	NGC3239	1	8	56	1	8	8	94.86	29.01	0.31	640	1.000
	M36	1	5	4	1	5	3	18.73	12.39	0.66	65	0.102
	M63	1	10	34	1	10	6	84.70	29.52	0.35	520	0.813
	NGC 1333	1	10	30	1	10	4	79.57	24.11	0.30	420	0.656
Imager #3	Arp 284	1	10	4	1	10	2	29.05	17.04	0.59	100	0.156
Imager #4	NGC5746	1	12	15	2	4	8	62.70	46.97	0.75	276	0.431
	NGC4261	1	12	14	2	4	8	60.57	46.97	0.78	264	0.413
	NGC4654	1	12	16	2	4	8	64.76	46.97	0.73	288	0.450
Imager #5	IC2574	1	10	36	1	10	20	87.16	53.90	0.62	960	1.500
	B22	1	10	28	1	10	6	76.87	29.52	0.38	460	0.719
Imager #6	M27	1	10	21	2	15	8	66.57	103.50	1.55	570	0.891
	NGC5033	1	20	38	2	15	20	133.59	163.64	1.22	1660	2.594
	NGC3371	1	20	27	2	15	12	112.61	126.76	1.13	1080	1.688
Imager #7	NGC7380	1	8	11	2	6	15	42.04	83.19	1.98	358	0.559
Imager #8	UGC1281	1	5	24	2	5	13	45.88	69.12	1.51	315	0.492
	NGC1160	1	5	10	2	5	5	29.62	42.87	1.45	125	0.195
	NGC925	1	5	15	2	5	12	36.27	66.41	1.83	255	0.398
Imager #9	NGC1333	1	20	30	2	20	13	118.70	154.43	1.30	1380	2.156
	VdB-142	1	20	7	2	20	8	57.34	121.14	2.11	620	0.969
Imager #10	NGC891	1	10	47	2	10	20	99.59	130.17	1.31	1070	1.672
Imager #11		1	10	16	2	10	8	58.11	82.33	1.42	400	0.625
		1	10	32	2	10	8	82.18	82.33	1.00	560	0.875
Dave Pearson	BIN 1 Ref	1	10	16	1	10	16	58.11	48.21	0.83	640	1.000
	BIN 2 Ref	1	10	16	2	10	16	58.11	116.43	2.00	640	1.000
		1	10	18	2	5	18	61.63	81.33	1.32	450	0.703

Image Capture Strategies (continued)

Some Image Capture Strategies and definitions.

1) RGB Only
    - Color Camera or R,G,B with mono Camera
        - Can use Synthetic Luminance during processing
2) Background Limited exposures
3) SNR diminishing returns
4) Equal Luminance and RGB exposure time
5) Equal Luminance and RGB SNR
6) Maximize exposure and number of Subs until Happy with object detail
7) Luminance to RGB SNR ratio
8) Binning with options 2) through 6)

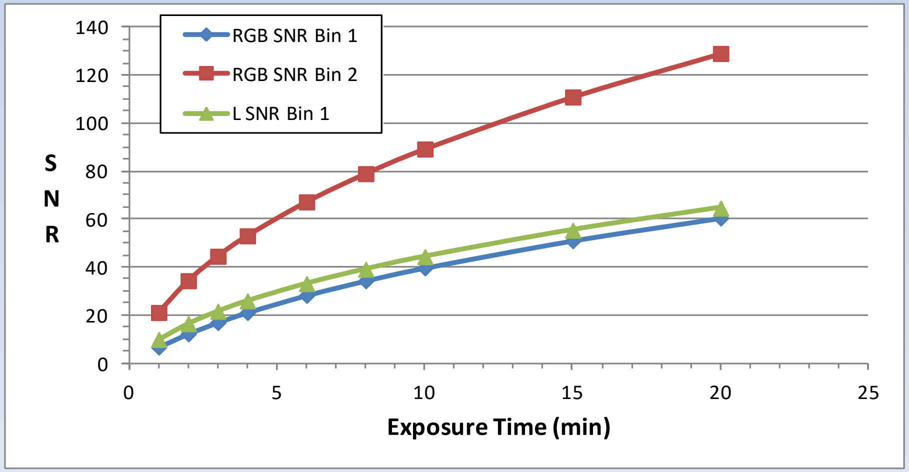
- RGB – Red, Green, Blue; three colors that can be used to create other colors. Each color created by using one of the R, G, B individual filters
- Luminance – all colors, but usually has frequency clipping on the lower and upper wavelengths to bound the wavelength transmission
- Synthetic Luminance – combine R, G, B images to create a Luminance image
- Maximum Exposure time is at the limit of equipment or whether the sub exposure time is being limited to maximize sub keep percentage
- Minimum Exposure time is when sufficient SNR with one sub is obtained for object being imaged (Signal at some level above Read Noise)

Image Capture Strategies (continued)

Before the discussion of Image Capture Strategies, Binning needs to discussed to provide context for the remainder of this section. In the definition section Binning was defined as

Pixel Binning – According to Wikipedia (https://en.wikipedia.org/wiki/Data_binning) , "…binning is the procedure of combining a cluster of pixels into a single pixel. As such, in 2x2 binning, an array of 4 pixels becomes a single larger pixel…." Binning is used to increase signal at the cost of a lower resolution.

- For BIN 1 - Even though the combined R, G & B signal approximately equals the Luminance (L) signal, the RGB SNR is lower than L SNR because read noise was in each of the R, G and B producing 3x read noise of L.



- For BIN 2, 4 pixels are combined to create four times the signal. But since noise is signal$^{1/2}$ the SNR only approximately doubles. Normally read noise is per pixel, but with bin 2 the data is read just once creating a 1x read noise

$$SNR_{BIN2} = \frac{4*Signal}{\sqrt{4*Signal}} = \frac{4*Signal}{2\sqrt{Signal}} = \frac{2*Signal}{\sqrt{Signal}}$$

Image Capture Strategies (continued)

6. Luminance to RGB SNR ratio (continued)

Binning (continued)

- Beware camera manufactures may limited the signal increase with Binning. So check with the manufacture before assuming the amount of signal increase over BIN 1

- The creation of the larger pixel reduces the camera resolution by two.
  - BIN 2 doubles image scale reducing resolution and may not meet nyquist sampling criteria causing image under sampling. Severity of resolution loss is dependant of seeing conditions, the amount of under sampling, and effectiveness of any under sampling correction algorithms

Image Capture Strategies (continued)

Analysis Overview

- The remaining charts will show the key parameter sensitivity of various image capture strategies.
  - Key parameters
    - SNR, Total exposure time
    - Performance indicators
      - Total exposure time ratio, RGB/L SNR ratio

First a dim target (case 1) will be assessed without Binning. Later the remaining cases w/wo Binning will be discussed to demonstrate possible differences.

	Signal (e-/min/sub)		
	Obj	**Sky**	**DC**
Case 1	30	3	1
Case 2	15	3	1
Case 3	100	3	1
Case 4	100	50	1
Case 5	100	100	1
Case 6	100	300	1
Case 7	100	500	1

Reference Image Capture Strategy

- Luminance, Red, Green, Blue Binned 1, each 10 min subs and 16 subs
  - Total Exposure time reference = 640min
  - Total Exposure time ratio = 1.0
- Rationale: 1) 10m subs are typical middle exposure times for high end astrophotography equipment in dark skies and to keep a high sub keep percentage, 2) 16 subs reduces noise to 25% of a single sub; to reduce by 1/square-root 2 needs 32 subs or adds 160 minutes per filter which is a large time penalty to double SNR. 16 subs is also the minimum subs for the recommended PixInsight image rejection logic algorithms for large number of subs. Same exposure time for L and RGB produces about the same SNR.

Note: The selection of reference sub exposure time and number of subs are completely arbitrary and were selected to allow consistent analysis. Same conclusions are obtained for any other set of values. RGB/L SN ratio = 1 was chosen as an indicator for color reference is user preference

Image Capture Strategies (continued)

1) **RGB Only**
   - Color Camera
     - Using a Color camera reduces the LRGB filter count from 4 to 1 because color cameras have a RGB filter build in. This reduces the total exposure time ratio to 0.25. Although color cameras generally required more total exposure time to get color in stars. So realistically the total exposure time ratio reduces to 0.50.
     - Not recommended to Color camera as already has lower resolution unless sky seeing is poor enough that it doesn't matter (see section on Resolution)

   - R,G,B with mono Camera
     - This strategies reduces number of filters from 4 to 3, so the total exposure time ratio is equal to 0.75.
     - Not recommended to BIN R,G,B with mono camera since no BIN 1 luminance unless sky seeing is poor enough that it doesn't matter (see section on Resolution)

Image Capture Strategies (continued)

2) Background Limited exposures

The individual R, G, B channels (bin 1) will have approximately 1/3 the flux of Luminance. Therefore, the individual R, G, B channels (bin 1) will become background limited at 3x Luminance sky limited time.

If RGB (bin 2) is used, the RGB signal will be approximately 4x the BIN 1 RGB value (4/3 of L flux), which then will become background limited at 0.75 (1 over 4/3) of the Luminance sky limited time.

Binning RGB 2 does reduce the time to achieve a sky limited background

Note: this effect is the same for any value of sky background

Image Capture Strategies (continued)

3) SNR diminishing returns

- This was covered in previous section, but here is summary using the same signals for cases 1-7. Remember the SNR from the target, sky and DC are combined for SNR diminishing returns analysis.

% SNR change for exposure time (min)

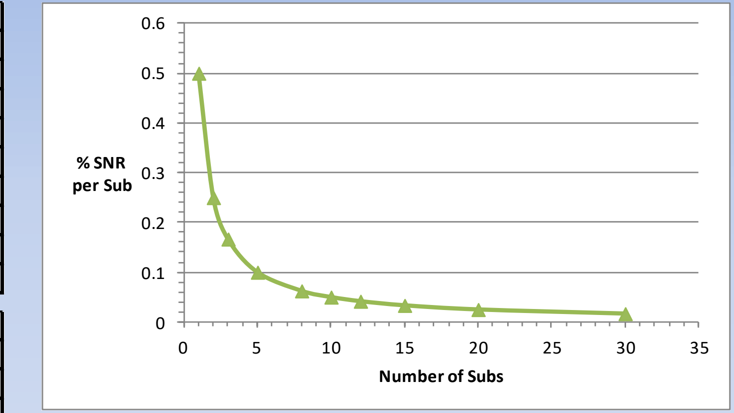
		Rnoise = 4 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	34	5.4	10.4	20.4
	19	5.6	10.7	20.8
	104	5.1	10.1	20.2
	151	5.1	10.1	20.1
	201	5.1	10.1	20.1
	401	5.0	10.0	20.0
	601	5.0	10.0	20.0

		Rnoise = 9.3 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	34	6.4	11.8	22.1
	19	7.0	12.6	23.3
	104	5.6	10.7	20.8
	151	5.5	10.5	20.5
	201	5.4	10.4	20.4
	401	5.2	10.2	20.2
	601	5.1	10.1	20.1

		Rnoise = 18 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	34	7.8	14.0	25.4
	19	8.4	15.3	27.6
	104	6.6	12.1	22.4
	151	6.3	11.6	21.8
	201	6.1	11.3	21.4
	401	5.6	10.7	20.7
	601	5.5	10.5	20.5

		Rnoise = 36 (e-)		
		% SNR Change		
		0.1	0.05	0.025
Total Starget+ Ssky+ DC	34	9.0	16.9	31.0
	19	9.4	17.9	33.4
	104	8.0	14.6	26.4
	151	7.6	13.8	25.1
	201	7.3	13.3	24.2
	401	6.6	12.1	22.5
	601	6.3	11.6	21.8

% SNR change for # of subs



Remember the total % SNR change is the combination of % SNR change for exposure + % SNR change for subs. Therefore, a 5% SNR change in exposure + subs = 10% total SNR change.

Image Capture Strategies (continued)

4. Equal Luminance and RGB exposure time (assumes equal number of subs)

- This strategy is the reference condition which has equal exposures time for each of the L, R, G & B filters. Obviously, this strategy does not reduce the total exposure times from that quoted in the previous section.
  - Equal BIN 1 RGB and L exposure times,
    - L SNR = 58 and the combined RGB SNR = 48, RGB/L SNR ratio = 0.83.
    - Total exposure time ratio = 1.0

  - BIN2 RGB condition,
    - L SNR = 58 and the combined RGB SNR = 115.7, RGB/L SNR ratio = 2.0.
    - Total exposure time ratio = 1.0

Image Capture Strategies (continued)

5. Equal Luminance and RGB SNR

- As noted previously the BIN 1 SNR of L=58, and the combined RGB SNR =48. Therefore with this strategy to achieve equal SNR either the RGB exposure must be increased to 13.2 min or the L SNR must be decreased to 7.3 min. So total exposure time ratio for increasing RGB is 794 min (1.24x) or by decreasing L is 597 min (0.93x). In both cases RGB/L SNR ratio = 1.0

- With a RGB BIN 2, everything becomes more complicated. RGB BIN 2 has twice the SNR of L, therefore either the RGB exposure time must decrease or the L exposure time or subs must increase to obtained the same SNR with both L and RGB.

    - Reducing RGB exposure time to 3.3 min or 4 subs provides a RGB SNR=58 with L SNR=58. Total Exposure time ratio=0.5 or 0.44

    - Increasing L exposure time to 34 min or 63 subs provides a L SNR= 115.7 with RGB SNR=115.7. Total Exposure time ratio=1.6 or 1.7.

Image Capture Strategies (continued)

6. Maximize exposure and number of Subs until Happy with object detail

- This strategy is self explanatory. Do anything until happy with object detail and all the theory is ignored. Nothing wrong with this approach! As long as picture is liked!

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio

- This strategy is really exploring the "equal L and RGB SNR" in more detail. Of all the strategies discussed this was the one that decreased the total exposure time the most. Although using a color camera or shooting only RGB was a close second and third.

- This strategy also tries to put a measuring stick on the quote at the beginning of this section.

  "We can (and should) sacrifice SNR in chrominance to boost SNR of luminance"

- As mentioned in the beginning of this section, two independent parameters called "**RGB/L SNR ratio**" and "**Total Exposure Time ratio**" were created.
  - In an attempt to understand the above quote and in a broader scope the relationship between various "Image Capture Strategies (Binning, sub exposure time and number of subs of LRGB)" and how each affect SNR and total exposure time

    - RGB/L SNR ratio – combined RGB SNR divided by Luminance SNR
      - **Provides an indicator of Color Strength using SNR**
    - Total Exposure Time ratio – Total exposure divided by 640 min (reference total exposure)

Image Capture Strategies (continued)

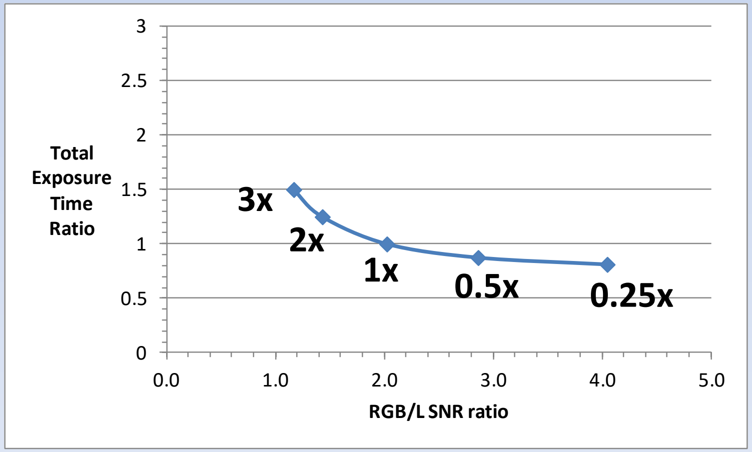
7. Luminance to RGB SNR ratio (continued)

Graph and Variable Definitions

- The curve below depicts the relationship between total exposure time and RGB/L SNR. The baseline case, referred to as 1x, is 10 min subs for L, R, G and B with 16 subs each for a total exposure time of 640min.

- Depending on the graph label, Every “x” value is either the # of subs multiplier or the sub exposure multiplier. For example, 2x denotes 2*16 subs or 32 subs, 0.25x multiplier denotes, 0.25*16 subs or 4 subs; 2x denotes 2*10min or 20min, 0.25x multiplier denotes, 0.25*10 min or 2.5 min.

- To obtain the total exposure time, the total exposure time ratio is multiplied by 640 min.



- The RGB/L SNR ratio is used as an indicator of the amount of Color. The larger the ratio, the higher the RGB SNR compared to L SNR. Higher RGB SNR for a given Luminance SNR will produce brighter colors.

Case 1

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Total Exposure time vs RGB/L SNR (BIN 1) as a function of number of subs

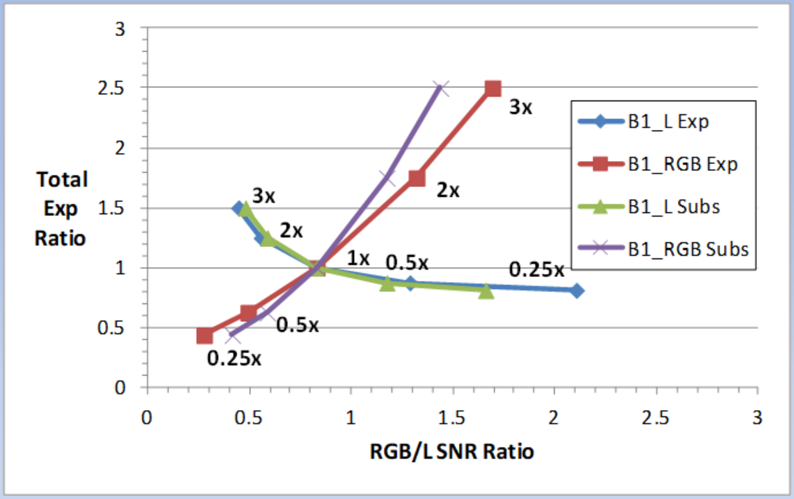


Image Capture Reference (1x) – Case 1

	Lum	R,G,B
Exp (min)	10	10
Subs	16	16
Obj Signal (e-/min/sub)	30	10
Sky Signal (e-/min/sub)	3	1
DC Signal (e-/min/sub)	1	1
Total Exp Time = 640min		

- Total exposure time can be reduced below the image capture reference values by reducing exposure time or the number of subs for either RGB or Luminance.
  - (lower left on chart) Reducing RGB subs/exposure provides substantial total exposure time reductions at the expense of RGB/L SNR ratio. This RGB/L SNR ratio reduction indicates a low color indicator.
  - Notice that reducing subs instead of exposure, slightly increases the RGB/L SNR ratio for a higher color indicator. However, if decreasing the RGB/L SNR ratio is desirable, then reducing exposure time would be a better choice.
  - (lower right on chart) Reducing Luminance exposure time provides a slight total exposure time reduction below the total exposure reference time with an increase of the RGB/L SNR ratio, which indicates a higher color indicator.
  - (upper left on chart) Increasing Luminance exposure or subs increases the total exposure time fairly quickly and also reduces the RGB/L SNR Ratio for a low color indicator. Not a good option for reducing total exposure time.
  - (upper right on chart) Increases the color indicator, but substantial increases the total exposure time for a high color indicator.

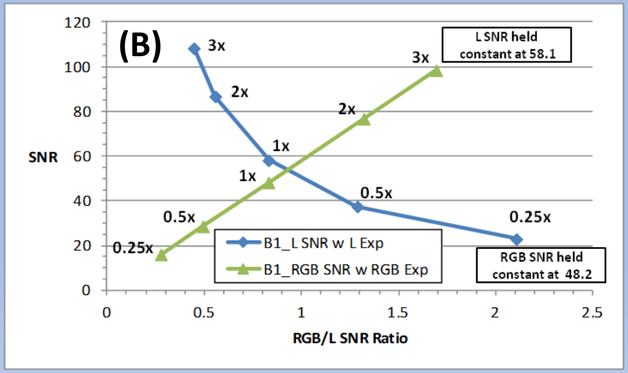
BIN 1 Summary; If it is believed that to get the best visual detail from an image requiring a higher SNR in Luminance than RGB, then the only options that exist is when RGB/L SNR ratio is below 1. When the RGB/L SNR ratio is below 1, there are two questions to answer; 1) how much color is needed in the image to be sky realistic or a pretty picture in your mind's eye, and 2) how much luminance SNR is required above RGB SNR? If you don't believe the above, then use a color camera or shoot only R,G,B.

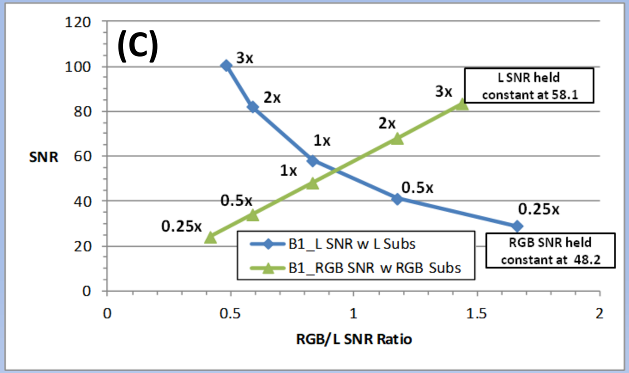
Case 1

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Total Exposure time vs RGB/L SNR (BIN 1) as a function of number of subs/exposure





- Chart (B) shows the SNR sensitivity of L and RGB exposures times. The green line holds L SNR at the 1x value, and varies RGB exposure time. The blue line holds RGB SNR at the 1x value, and varies L exposure time.

- Chart (C) shows the SNR sensitivity of L and RGB Number of subs. The green line holds L SNR at the 1x value, and varies number of RGB subs. The blue line holds RGB SNR at the 1x value, and varies number of L subs.

Summary

- Reducing the Luminance exposure or subs substantially below the image capture reference values (lower right blue line in either graphs (B) or (C)) produces results with a very low Luminance SNR compared to RGB so it begs the question as why is Luminance being shot?
- Increasing the Luminance exposure or subs substantially beyond the image capture reference values (upper left blue line in either graphs (B) or (C)) results in very large L SNR compared to RGB, which supports using L for detail and RGB for coloring, but at an increase total exposure time.
- Increasing the RGB exposure or subs substantially above the image capture reference values (upper right green line in either graphs (B) or (C)) results in very large RGB SNR compared to L which supports using L for detail and RGB for coloring, but at a sever increase in total exposure time.
- Decreasing the RGB exposure or subs substantially beyond the image capture reference values (lower left green line in either graphs (B) or (C)) results in lower RGB SNR compared to Luminance which supports using L for detail and RGB for coloring and decreases the total exposure time.

Image Capture Reference (1x) – Case 1

	Lum	**R,G,B**
Exp (min)	10	10
Subs	16	16
Obj Signal (e-/min/sub)	30	10
Sky Signal (e-/min/sub)	3	1
DC Signal (e-/min/sub)	1	1
Total Exp Time = 640min		

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Summary

- Reducing RGB exposure time or subs is the only option that supports the supposition that L SNR should be higher than RGB for maximum detail with some color and reduces total exposure time.

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Effect of Binning

In the previous few charts the image capture strategies for BIN 1 was discussed.

Now lets bring in RGB BIN 2 and repeat the previous analysis to determine whether Binning provides additional options or better solutions than BIN 1.

We will assume the theoretical increase in SNR with BIN 2 and ignore any manufacturing signal limiting in any particular camera. After this assessment, manufacture signal limiting with BIN 2 will be addressed.

The following SNR equation was used.

$$SNR = \frac{\left(B^2\right) * N * t * S_{Target}}{\sqrt{N * \left(\left(B^2\right) * \left(t * \left(S_{Target} + S_{Sky} + DC\right)\right) + R_{Noise}^2\right)}}$$

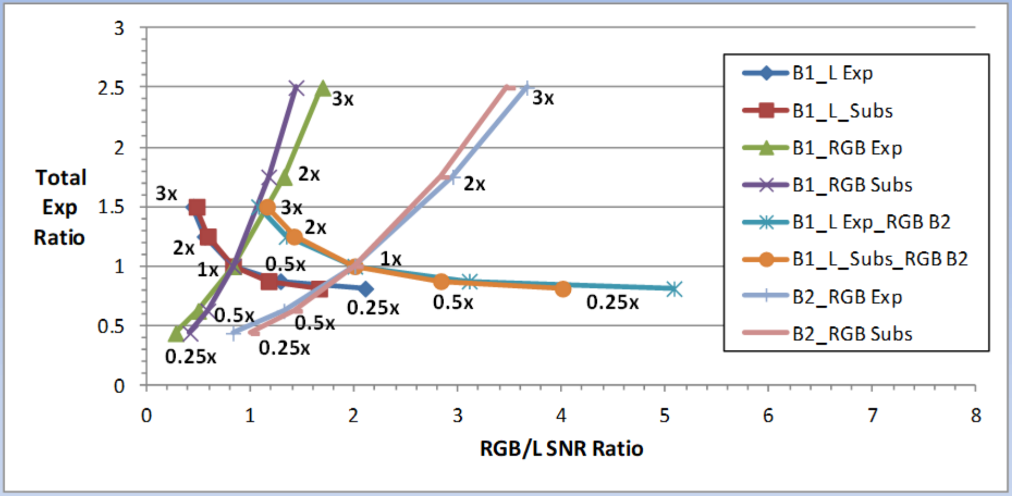
N - # of subs
t – exposure time
Starget – target or object signal
Ssky – Sky or background signal
DC – Camera Dark Current
Rnoise – Camera Read Noise
B – BIN 1 =1, BIN 2 = 2

Case 1

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Total Exposure time vs RGB/L SNR as a function of number of subs - RGB Bin 2



- It is seen that when BIN 2 is used on RGB, the curves move only to the right which increases the color indicator but total exposure ratio stays the same.
- This implies that BIN 2 RGB SNR can be used to trade for lower total exposure time and still make the color indicator higher than with BIN 1.

Image Capture Reference (1x) – Case1

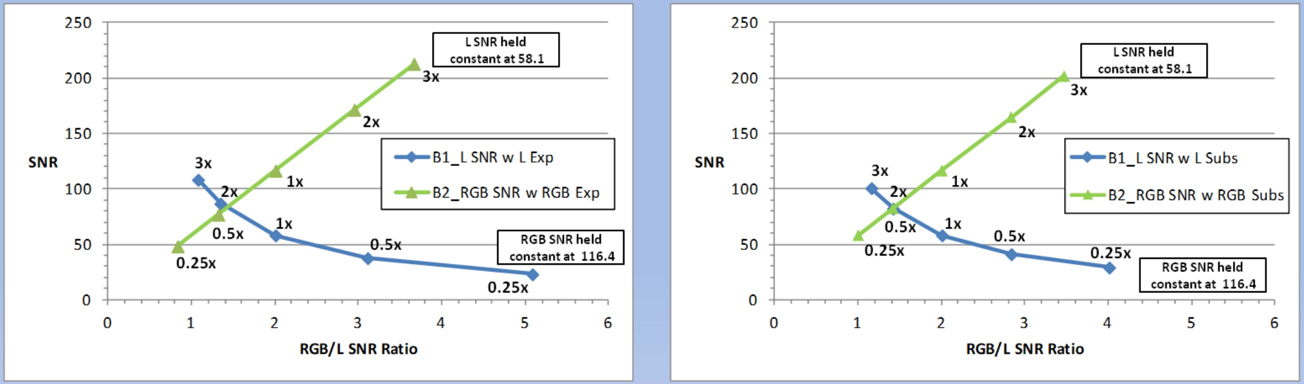
	Lum	R,G,B
Exp (min)	10	10
Subs	16	16
Obj Signal (e-/min/sub)	30	10
Sky Signal (e-/min/sub)	3	1
DC Signal (e-/min/sub)	1	1
Total Exp Time = 640min		

Case 1

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Total Exposure time vs RGB/L SNR as a function of number of subs/exposure - RGB Bin 2



- As expected with BIN 2 RGB, the Luminance line (Blue) stays the same, but the RGB line (green) approximately doubles in SNR and RGB/L SNR ratio
- If it is believed that to get the best visual detail from an image requires a higher SNR in Luminance than RGB, then the only options that exist is when RGB/L SNR ratio is below 1
    - With RGB BIN 2, the exposure or subs must be reduced to about 25% to get to the RGB/L SNR ratio=1. At this value, BIN 2 RGB SNR is about same as BIN 1 RGB, but total exposure time is 50% of BIN 1 (previous chart).
    - Then by trading total exposure to increase L subs/exposure to further reduce the RGB/L SNR ratio and increase the L SNR further above the RGB SNR.

Image Capture Reference (1x) – Case1

	Lum	R,G,B
Exp (min)	10	10
Subs	16	16
Obj Signal (e-/min/sub)	30	10
Sky Signal (e-/min/sub)	3	1
DC Signal (e-/min/sub)	1	1
Total Exp Time = 640min		

Image Capture Strategies (continued)

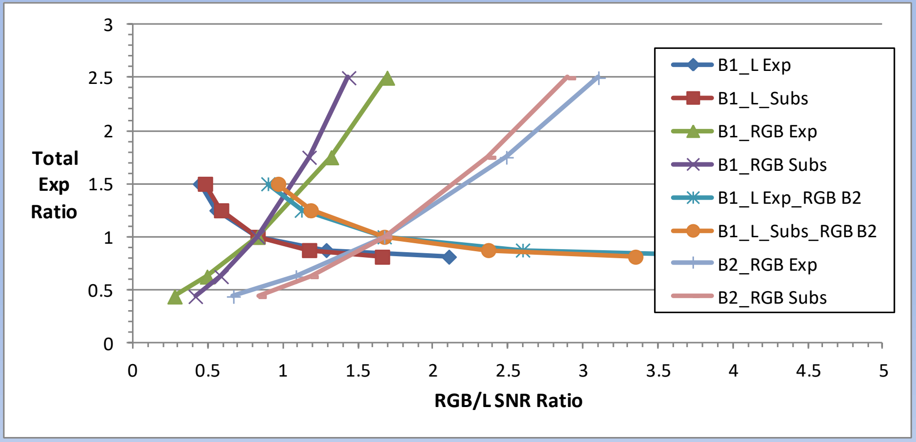
7. Luminance to RGB SNR ratio (continued)

What happens if the camera manufacture limits the BIN 2 signal to a value lower than theoretical?

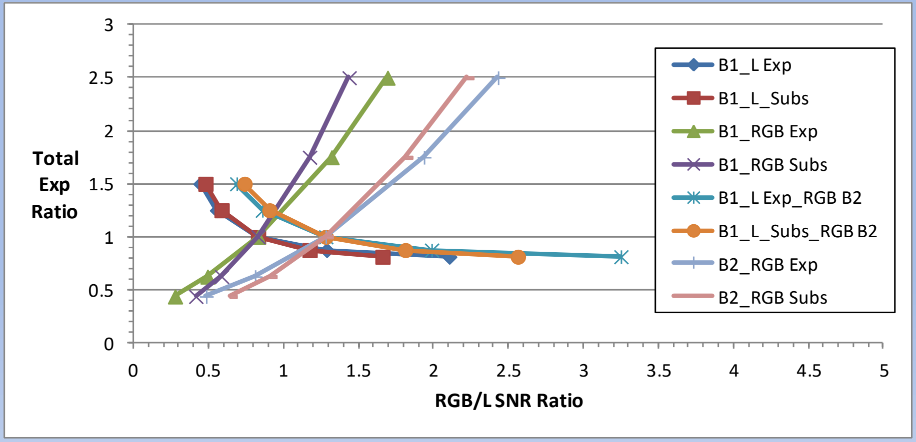
Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Effects of Camera Manufacturing BIN 2 Limiting



BIN 2 Signal limit:
75% of theoretical BIN 2 value



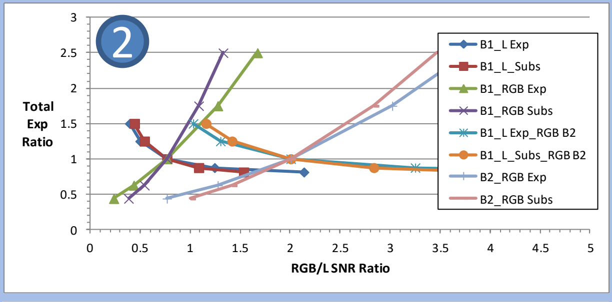
BIN 2 Signal limit:
50% of theoretical BIN 2 value

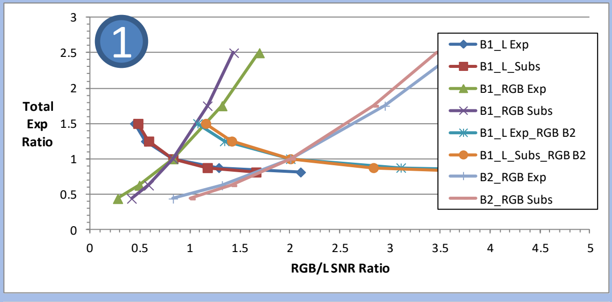
- Notice that if the RGB BIN 2 signal is limited by the camera manufacturer, the BIN 2 curves move to the left and get closer to the BIN 1 curves as should be expected.
- At 25% reduction
  - With the RGB BIN 2 exposure reduction of 0.5x and increasing the luminance subs to 2x, the conclusions from before still look good.
  - With the RGB BIN 2 exposure reduction to 0.25x, the RGB/L SNR ratio appears to reduce to very low levels, so maybe luminance subs should stay at 1x.
- At 50% reduction
  - Same conclusions as with a 25% reduction in RGB BIN 2
- At 75% reduction (not shown)
  - Luminance Subs should stay at 1x for both RGB exposures of 0.5x and 0.25x
- Beyond 75% reductions
  - Probably not worth RGB Binning

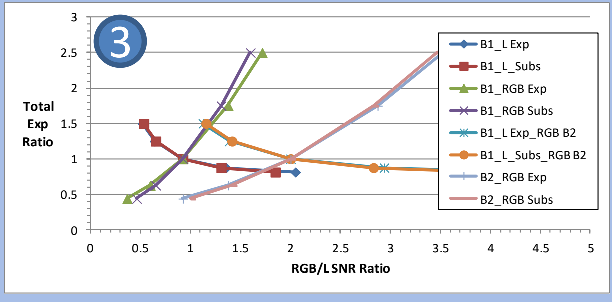
Image Capture Strategies (continued)

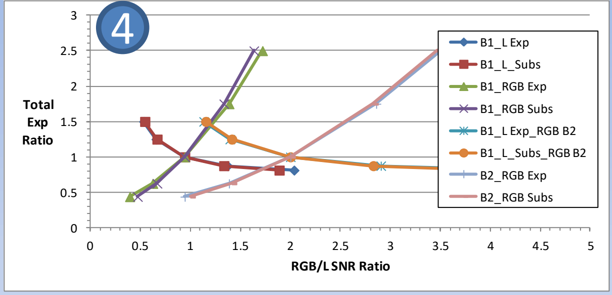
7. Luminance to RGB SNR ratio (continued)

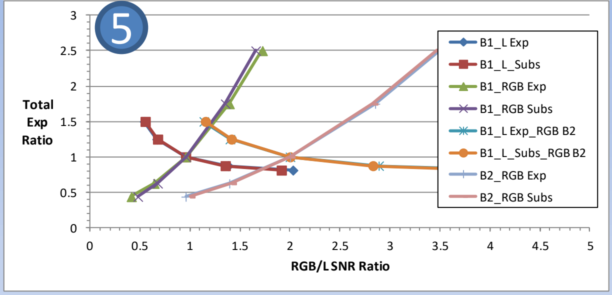
Signal Strength Variations

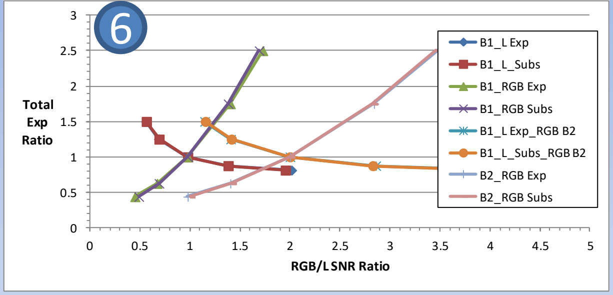


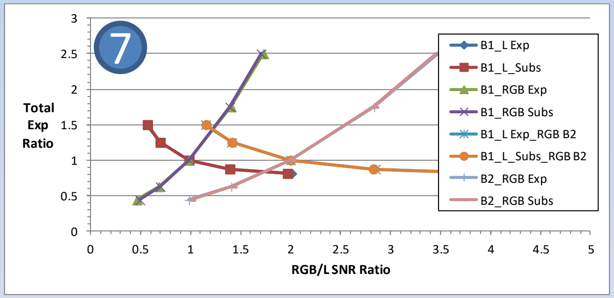












	Signal (e-/min/sub)			**L BIN 1**	**RGB B1**	**RGB B2**
	Obj	**Sky**	**DC**	**SNR**	**SNR**	**SNR**
Case 1	30	3	1	58	48	116
Case 2	15	3	1	36	28	72
Case 3	100	3	1	119	110	238
Case 4	100	50	1	100	95	200
Case 5	100	100	1	87	84	175
Case 6	100	300	1	62	61	125
Case 7	100	500	1	51	50	102

- As signal strength increases, the amount of RGB/L SNR ratio variation between Exposure time and number of subs becomes smaller as read noise is being swamped by signal
- RGB/L SNR ratio stays the same because input signal affects L and RGB the same
- As Sky noise increases, sever drop in SNR occurs, as would be expected.

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Summary/Recommendations/Regrets

							Signal Reduction			
Parameter	**Reference**	**Option A**	**Option B**	**Option C**	**Option D**	**Option E**	**25%**	**50%**	**75%**	**Opt. E BIN 1 Equilavent**
Luminance	B1 16x10m	B1 16x10m	B1 16x10m	B1 16x10m	B1 16x10m	B1 32x10m				B1 32x10m
RGB	B1 16x10m	B2 16x10m	B2 16x5m	B2 16x2.5m	B2 8x5m	B2 8x5m	(B2 8x6.8m)	(B2 8x10.5m)	(B2 8x23m)	B1 16x11.8m
Lum SNR	58	58	58	58	58	82				82
RGB SNR	48	116	76	48	54	54	45(54)	33(54)	19(54)	54
RGB/L SNR ratio	0.83	2	1.31	0.82	0.93	0.66	0.54(0.66)	0.41(0.66)	0.23(0.66)	0.66
Total Exp Time ratio	1	1	0.625	0.44	0.44	0.69	(0.76)	(0.89)	(1.36)	1.39
Total Exp Time (min)	640	640	400	280	280	440	(483)	(572)	(872)	886

(text) = Values required to be equivalent to theoretical BIN 2 SNR and RGB/L SNR ratio, and with total exp ratio/time impacts

- Option A - BIN 2 RGB to increase RGB SNR with respect to reference exp and subs
- Option B - Reduce B2 RGB exposure to 50% from reference to trade RGB SNR for total exposure time
- Option C - Reduce B2 RGB exposure to 25% from reference to trade RGB SNR for total exposure time
- Option D - Double B2 RGB exposure from option C to raise RGB SNR, and decrease RGB subs by 50% to maintain total exposure time
- Option E – Double Luminance Subs to raise RGB/L SNR ratio
- Opt. E BIN 1 Equivalent – BIN 1 values needed to match Option E BIN 2 image capture parameters with total exposure time impacts

Image Capture Strategies (continued)

7. Luminance to RGB SNR ratio (continued)

Summary/Recommendations/Regrets (continued)

- Detailed analysis in this section was for a relative dim object at a dark sky. However, a sensitivity analysis was performed to vary the object or target signal as a function of the sky signal. Results showed that the relative SNR differences between L and RGB did not change.
  - What did change was as the Sky noise increased there was a sever drop in SNR
  - Also as the signal increased, the amount of RGB/L SNR ratio variation between Exposure time and number of subs became smaller because the read noise was being swamped by signal
    - However, at low signals, there was a 7-9% variation in SNR depending upon whether SNR was being increased or decreased and to whether exp or number of subs were being changed.
    - The choice to increase subs or exposure depends on whether imager is trying to increase or decrease the SNR separation between RGB and L.
- The previous chart provides some guidance in how to select RGB and L exposure and number of subs depending upon what the imager desires; equal RGB & L SNR, or L SNR > R SNR or R SNR > L SNR
  - A good starting point would be use option D which gives a RGB/L SNR ratio ~1.0 and a 56% savings in total exposure time. Process the image and decide if color is sufficient, if not run some more subs. If color is sufficient, than may want to try adding more L subs, until color becomes unsatisfactory. If you think that Luminance SNR needs to be higher than RGB SNR to increase detail than use option E which still provides a 31% total exposure savings.

Image Capture Strategies (continued)

Summary

	Image Capture Strategy Options - Summary (case 1)														
Parameter	**Reference**	**1a. Color**	**1b. RGB**	**2a. Bkgrd limited (Bin 1)**	**2b. Bkgrd limited (RGB Bin 2)**	**3a. SNR Dim. Returns (10%)**	**3a. SNR Dim. Returns (5%)**	**4a. Equal RGB/L exp (Bin 1)**	**4b. Equal RGB/L exp**	**5a. Equal RGB/L SNR (Bin 1)**	**5b. Equal RGB/L SNR (Bin 1)**	**5c. Equal RGB/L SNR (RGB Bin 2)**	**5d. Equal RGB/L SNR (RGB Bin 2)**	**7a. RGB/L SNR ratio (RGB Bin 2)**	**7b. RGB/L SNR ratio (RGB Bin 2)**
Luminance	B1 16x10m	NA	NA	B1 16x22m	B1 16x22m	B1 10x12m	B1 20x22m	B1 16x10m	B1 16x10m	B1 16x10m	B1 16x7m	B1 16x10m	B1 16x34m	B1 16x10m	B1 32x10m
RGB	B1 16x10m	B1 16x10m (2-3x)	B1 16x10m	B1 16x66m	B2 16x33m	B1 10x12m	B1 20x22m	B1 16x10m	B2 16x10m	B1 16x13m	B1 16x10m	B2 16x3.3m	B2 16x10m	B2 8x5m	B2 8x5m
Lum SNR	58	NA	NA	91	91	51	102	58	58	58	48	58	116	58	82
RGB SNR	48	NA	48	153	222	43	90	48	116	58	48	58	116	54	54
RGB/L SNR ratio	0.83	NA	NA	1.7	2.4	0.84	0.88	0.83	2.0	1.0	1.0	1.0	1.0	0.93	0.66
Total Exp Time ratio	1.0	0.5-0.75	0.75	5.5	3.0	0.8	2.75	1.0	1.0	1.24	0.93	0.5	1.6	0.44	0.69
Total Exp Time (min)	640	320-480	480	X 3520	X 1936	480	X 1760	640	640	X 794	597	320	X 1024	280	440

- The goal of this section was to determine if total exposure time could be reduced and still achieve good color and/or good detail. Above is the Case 1 summary of everything discussed in this section. The options that do not reduce total exposure time are shown with a X. The remaining options cover almost the entire gambit of image capture strategies.
- The selection for you is dependent upon your mind's eye in achieving good color and good detail.
    - If you believe that L SNR should be above RGB SNR, then consider option 7b.
    - If option 7b is considered to be low in color than consider options 5c and 7a and save in total exposure time at the same time.
    - If options 5c and 7a is consider to still be low in color than start increasing the RGB exposure and/or subs until satisfied. These two options have a lot of total exposure time to trade for color.

Image Capture Strategies (continued)

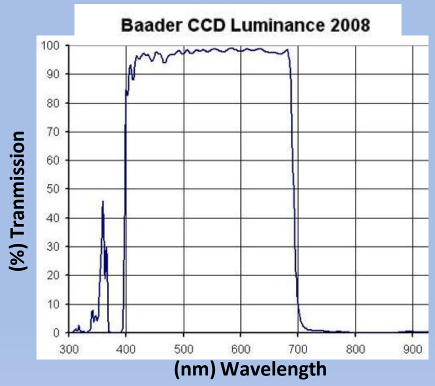
Summary (continued)

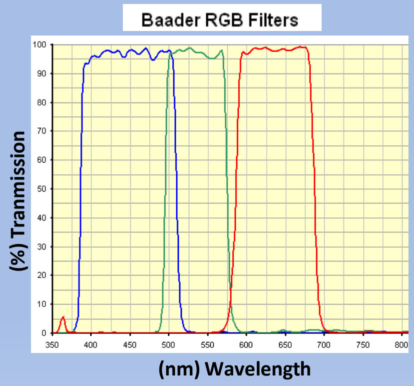
- A lot of discussion has been presented on how to reduce total exposure time by trading the BIN 2 RGB SNR. However, to be fair, the BIN 1 RGB exposure and/or subs could also be reduced to save total exposure time. However doing this will reduce RGB SNR to low values that may be unacceptable.

- Even though it is apparent in the benefits of RGB BIN 2, there are conditions when RGB BIN should not be used. Such as 1) a camera manufacture limiting BIN 2 by more than 50%, 2) objects (i.e. globular clusters) that require full resolution or 3) really good seeing.

- The next couple of charts will try to demonstrate that the combined RGB SNR is approximately equal to the L SNR.

Theoretical vs Actual Filter Transmission Analysis





https://www.teleskop-express.de/shop/BILDER/shop/Baader/Filter/RGB/Baader_L.jpg

http://www.company7.com/library/sbig/sbwhtmls/announcement_baader_lrgb_f2.htm

Curve integration

BIN 1	Hand Integrated	Graph Grapper [1]
Luminance	288.16	291.56
Red	----	101.95
Green	----	78.26
Blue	120.79	120.77
RGB	----	300.98
RGB/L	----	1.032

[1] https://www.quintessa.org/software/downloads-and-demos/graph-grabber-2.0

Image Xi Tau Star [2] test (2minutes)

- TPO RC 12 on AP1200
- SBIG STF-8300m (assumed read noise spec)
- LRGB Baader Filters
- ~64 deg elevation
- Captured 10/23/2017 2:48am to 3:17am

	Manual Calibration			PixInsight Calibration			Signal	
BIN 1	**Signal Mean**	**[3] SNR**	**RGB/L SNR ratio**	**Signal Mean**	**[3] SNR**	**RGB/L SNR ratio**	**Mean Error**	**SNR Error**
Lum	654.55	16.16	**----**	506.80	15.01	**----**	22.6%	7.2%
Red	281.45	8.40	0.52	228.50	7.78	0.52	18.8%	7.3%
Green	363.29	10.51	0.65	275.10	9.13	0.61	24.3%	13.2%
Blue	411.29	11.81	0.73	292.70	9.62	0.64	28.8%	18.6%
RGB	----	17.90	1.11	----	15.37	1.02	----	14.1%
BIN 2								
Red	730.23	18.79	1.16	581.90	16.63	1.11	20.3%	11.5%
Green	914.29	22.45	1.39	794.10	20.96	1.40	13.1%	6.7%
Blue	1162.72	27.61	1.71	907.90	23.06	1.54	21.9%	16.5%
RGB	----	40.24	2.49	----	35.32	2.35	----	12.2%

BIN 1

Manual Dark/Bias Calibration - RGB/L SNR ratio = 1.1

- 16 Dark and 256 Bias masters (mean values only)
- Background mean averaged 30 x (30x30 pixels), No hot pixels

PixInsight Calibration – RGB/L SNR ratio = 1.02

- 16 Dark/Flat masters, 256 Bias masters

BIN 2

	Manual	PixInsight
RGB/L SNR ratio	2.49	2.35

Using PixInsight calibration BIN 1 signal values estimated BIN 2 SNR using 4 (2x2) pixels – RGB SNR=44.7 with RGB/L SNR ratio of 2.97, therefore manufacture limits signal to equivalent of 2.86 pixels, or 27% SNR loss, or 39% signal loss from theoretical value

[2] Star Spectra B9Vn (-0.07, blue-white) – Therefore, was unable to confirm individual R,G,B filter transmission compared to Luminance. Need a G2V star.

[3] $$SNR = \frac{(B^2)*N*t*S_{Target}}{\sqrt{N*((B^2)*(t*(S_{Target}+S_{Sky}+DC))+R_{Noise}^2)}}$$

N - # of subs, t – exposure time, Starget – target or object signal, Ssky – Sky or background signal

DC – Camera Dark Current, Rnoise – Camera Read Noise, B – BIN 1 =1, BIN 2 = 2

Theoretical vs Actual Filter Transmission Analysis - Summary

- BIN 1, RGB/L SNR ratio was similar for the SBIG transmission curve integration (1.03), and an actual star test for both manual (1.11),and PixInsight calibration (1.02).
  - Actual RGB signal strength after PixInsight calibration was lower by 23% for L, 19% for Red, 24% for Green and 29% for Blue when compared to Manual calibration
    - One possible explanation is while calculating background from raw image, hot pixels were excluded. This may of artificially increased the calibrated signal when compared to the signal after calibration by PixInsight
  - BIN 1 theoretical calculations assuming that each R, G, and B filter is 0.33x luminance, resulted in a RGB/L SNR ratio of 0.84.
    - Raising the RGB/L SNR ratio to 1.02 to be compatible with the PixInsight calibration result from above, requires that each R,G,B filter is 0.44x of luminance. This implies that each of the RGB filters is passing 33% more light than expected.
    - After PixInsight calibration the average of the R, G and B filter signal reduction were 0.48x luminance, resulted in a RGB/L SNR ratio of 1.09. Which implies 45% more light being passed than expected.
- Obviously, these results are not as expected and are not consistent.
  - It was determined that star was saturated in every filter
  - So more data needs to be collected to resolve this discrepancy!

Agenda

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    - Calibration and Stacking
    - The Darker the Skies, the better the Image
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Resolution

Implication of Binning on Resolution

- As a generally rule, to obtain a deep sky image with great detail requires an image with great resolution. However, a large portion of astroimagers bin their RGB images to achieve higher SNR and shorter total exposure times. And of course a 2x2 binning (Bin 2) will reduce the resolution by 2.

- To try to reduce the resolution loss, Luminance can be shot with Bin 1, and then combined with the RGB Bin 2. This of course provides a final resolution somewhere between of the L Bin 1 and RGB Bin 2 depending on the SNR of each.
  - As a note, according to prediction as described previously, the assumption that L and RGB have equal exposure times and R,G,B each has 33% of L signal, RGB Bin 1 has about 1.12x more noise than L, and RGB Bin 2 has about 2x more noise than L
- As could be surmised, this indicates that L should have a higher SNR than the lower resolution and higher noise of RGB Bin 2 images.

But is it true that for all telescope/camera/mounts and all seeing conditions that Binning reduces image resolution?

Resolution (continued)

Image Quality

A telescope/camera produces a maximum resolution that is dependent on

- The aperture, type and quality of the telescope optics, telescope/camera collimation, temperature between optics and ambient air, and the application of Nyquist to the camera/telescope image scale – Optics error
- For time exposures, the quality of the peak-to-peak tracking which includes polar alignment, vibration caused by wind– Tracking error
- Atmospheric seeing (atmosphere scintillation) – Seeing Error

- These resolution components approximately combine as a quadratic sum to yield the inherent image resolution of a Telescope/camera system imaging through the atmosphere:

Image resolution or image spot size = sqrt(Seeing^2 + Tracking error^2 + Optics error^2)

- Several other equations that are important in this discussion are the following:

  - Bin 1 Image scale = 206.265*PixelSize (microns)/FocalLength (mm)
  - Bin 2x2 Image scale = 2* Bin 1 Image scale
  - Nyquist = Image resolution or spot size/image scale (more info at http://starizona.com/acb/ccd/advtheorynyq.aspx)

Portions taken from http://www.stanmooreastro.com/pixel_size.htm

Resolution (continued)

Using Nyquist to Measure Image Quality w/wo Binning

Nyquist refers to the sampling frequency required to reconstruct audio waves (sound). Nyquist sampling requires an audio wave to be sampled at least twice the audio frequency to reconstruct an audio wave. So what is the image reconstruction equivalent? That is another astro-imager controversy. But the majority of folks would say some where around 2.5 and 3.3, depending on the assumptions and how the math is performed.

Now let's begin to determine the image resolution or spot size.

Seeing - Seeing error is going to be our independent variable and will be used parametrically.

Tracking - Tracking accuracy for my AP1200 mounting with auto guiding is about 0.75 arcsec peak-to-peak

Optical Error - Optical Error is a combination of several terms and generally doesn't lend itself to easily turn the error into a seeing error except through the use of the FWHM spot size. According to Wikipedia, "The FWHM of the point spread function (loosely called seeing disc diameter or "*seeing*") is a reference to the best possible angular resolution which can be achieved by an optical telescope in a long photographic exposure, and corresponds to the FWHM of the fuzzy blob seen when observing a point-like source (such as a star) through the atmosphere.".

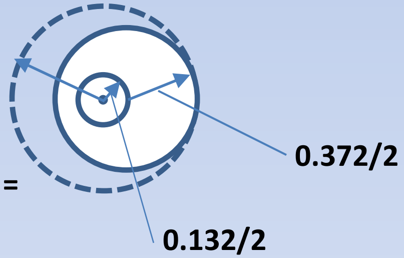
Resolution (continued)

Using Nyquist to Measure Image Quality w/wo Binning

First we will approximate the FWHM under perfect seeing through a perfect telescope using the airy disk diameter, which is defined by λ/D. λ is wavelength of light, which will assumed here to be 550nm, and D is the telescope diameter in meters. This equation is close to the Dawes empirical derived resolution limit.

- So for a D=.305m, the airy disk diameter or FWHM = 1.8033x10-6 radians or 0.372 arc-sec.
- Lets assume the optics are good to ¼ peak-to-peak of the wavelength of light. That means an error of 0.093 arc-sec per surface. My telescope has two surfaces so the error is sqrt(0.093^2+0.93^2) = 0.132 arc-sec. If this is the error of the optics, it also means that I can't collimate to a better measured accuracy than this.

  - The Bin 1 image scale = 206.265*5.4 microns/1700mm = 0.655 arc-sec.
  - The 2x2 Bin image scale = 1.31 arc-sec



Airy disk + Optic Accuracy =
0.372/2+0.132/2=0.252

- So therefore my total error is 2*sqrt((0.5*0.372+0.5*0.132)^2+0.5*0.132^2)) =
  2*sqrt(0.252^2+0.066^2)=2*0.260 =0.521 arc-sec
- My pixel size is 0.66 arc-sec, so optical error is within the size of one pixel. Because of the uncertainty of my ballpark estimates, I will assume that the optical error for bin 1 is 1 arc-sec and for Bin 2 1.5 arc-sec. Assumption is the telescope lens or mirrors are at same temperature and no vibration caused by the wind.

Resolution (continued)

Best resolution with camera and telescope
Camera Pixel Size Fixed

Seeing (arc-sec)	Bin 1 Spot Size (arc-sec)	Equivalent Nyquist (Bin 1) IS = 0.66 arc-sec/pixel	Bin 2 Spot Size (arc-sec)	Equivalent Nyquist (Bin 2) IS = 1.31 arc-sec/pixel
3	3.25	4.9	3.44	2.6
2.5	2.80	4.2	3.01	2.3
2	2.36	3.6	2.61	2.0
1.5	1.95	3	2.25	1.7
1	1.60	2.4	1.95	1.5

- Tracking Error = 0.75 arc-sec peak-to-peak, AP1200 mount with Auto Guiding
- Optical Error = 1 arc-sec Bin 1, 1.5 arc-sec Bin 2
- Red Numbers indicate $< \text{Nyquist}_{\text{minimum}} = 2.5$

Depending on seeing while Binning, Nyquist may not be met and image will be under sampled causing resolution to degrade.

Resolution (continued)

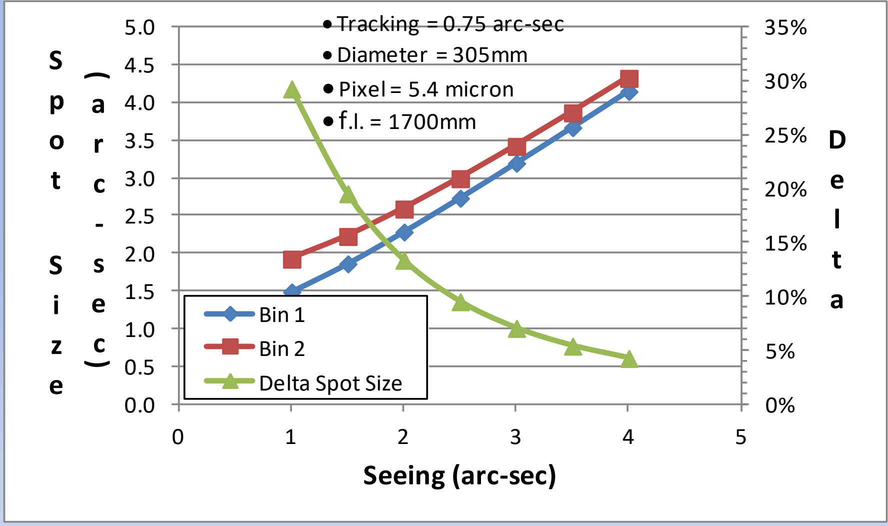
To Maintain Nyquist with Binning, Focal Length must be Increased

Seeing (arc-sec)	Bin 1 Spot Size (arc-sec)	Focal Length (mm) (Bin 1) Image Scale(IS) = 0.66 arc-sec/pixel		Bin 2 Spot Size (arc-sec)	Focal Length (mm) (Bin 2) IS = 1.32 arc-sec/pixel	
		Nyquist=2.5	Nyquist=3.3		Nyquist=2.5	Nyquist=3.3
3	3.25	857	1131	3.44	1619	2137
2.5	2.80	996	1315	3.01	1850	2442
2	2.36	1181	1558	2.61	2134	2817
1.5	1.95	1426	1882	2.25	2475	3267
1	1.60	1740	2296	1.95	2856	3770

- Tracking Error = 0.75 arc-sec peak-to-peak
- Optical Error = 1 arc-sec Bin 1, 1.5 arc-sec Bin 2

Resolution (continued)

Binning may not Reduce Resolution in all Seeing Conditions



Spot size = sqrt(seeing^2+tracking error^2+optics error^2)

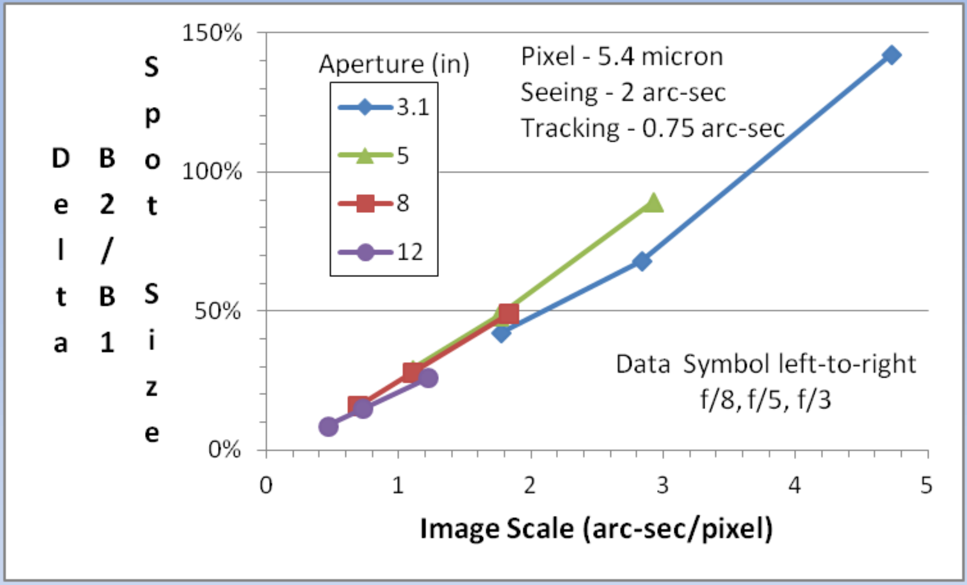
•At 2 arc-sec seeing, Bin 2 only increases spot size by 13.4%.

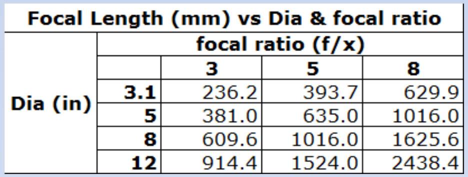
•At 4 arc-sec seeing, Bin 2 only increases spot size by 4.2%.

- My hypothesis,
  - That above data is valid when the L Bin 1 and RGB Bin 2 SNR are the same
  - When combining L Bin 1 and RGB Bin 2 at the same SNR, the resulting resolution would be between Bin 1 and Bin 2 values. As L SNR gets larger than RGB SNR, the delta spot size(green curve) approaches zero or Bin 1 resolution. And conversely, as RGB SNR gets larger than L SNR, the resolution approaches the Bin 2 value. For this example at my typical seeing conditions at 2 arc-sec, these result say that binning is costing me only 6.7% resolution assuming L and BIN 2 RGB SNR is the same.

Resolution (continued)

Binning Comparison for Different Telescope/Camera Configurations





Focal Length (mm) vs Dia & focal ratio

		focal ratio (f/x)		
		3	**5**	**8**
Dia (in)	**3.1**	236.2	393.7	629.9
	5	381.0	635.0	1016.0
	8	609.6	1016.0	1625.6
	12	914.4	1524.0	2438.4

As expected, the smaller the Image Scale, the less effect Bin 2 has on the FWHM or Spot size for a given Seeing, Tracking and Optical errors.

Resolution (continued)

Summary

- BIN 2 reduces the image resolution by a factor of 2.
- Without increasing telescope focal length while using BIN 2, the image will be undersampled. So native resolution is reduced by 2 and the image may be undersampled too. There is an algorithm developed to improve undersampled images(drizzle), but it is only an improvement, it can't reproduce the image back to the exact original.
- Seeing conditions and the image scale define the amount of resolution actually lost while using BIN 2.
    - The effect of using BIN 2 does not automatically dictate that the actual observed resolution is cut in half.

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Summary

Methods of Improving SNR

- Calibrating CCD images involves removing noise artifacts and uneven illumination. This is done by taking dark frames, bias frames, and flat field images.

- Stacking is used to increase the signal to noise ratio

  The signal is measured repeatedly n times and then averaged.

$$\bar{y}=\frac{1}{n}\sum_i y(t)_i = x(t)+\frac{1}{n}\sum_i w(t)_i$$

  Assuming that the noise is white and that its variance is constant in time it follows by error propagation that

$$\sigma(\bar{y})=\frac{1}{\sqrt{n}}\sigma$$

  Thus, if 100 measurements are averaged the signal to noise ratio is increased by a factor of 10, and the sigma noise reduced by 1/10.

- With the SBIG STF-8300 low dark current (DC) and read noise < ~10 photons, data suggests that calibration Darks may not be necessary at all temperatures and Exposure Times

Summary (continued)

Methods of Improving SNR (continued)

- The Darker the Skies, the better the Image. Several sources to determine the light pollution in your observing area are listed below.
    - **www.cleardarksky.com**
    - **DarkSiteFinder.com/maps/World.html**
- Example was provided on how to estimate the sky background flux and compare to measurement.

Summary (continued)

Defining SNR with and without Stacking

- Signal-to-Noise-ratio (SNR) equation was define that included effects of stacking

$$SNR = \sqrt{N}\,\frac{t * S_{Target}}{\sqrt{t * \left(S_{Target} + S_{Sky} + DC\right) + R_{Noise}^{2}}}$$

SNR – Signal-to-Noise Ratio
N – number of subs of equal duration, equal temperature and binning
t – multiples of Sub duration, equivalent to minutes if sub duration is 1 minute
Starget – Target signal with sky background (Including DC and bias) removed
Ssky – Sky signal with DC (Including bias) removed
DC – Dark Current with Bias removed
Rnoise – Camera Read Noise

$$\begin{aligned} where\ \ S_{Target} &= \text{Target} - Sky \\ S_{Sky} &= Sky - Dark \\ DC &= Dark - Bias \end{aligned}$$

- Analysis was provided to Verify that noise is the square root of the signal

Summary (continued)

Defining SNR with and without Stacking (continued)

- Image Combine Methods consist of two distinct parts: Rejection and combination

  - The goal of a pixel rejection algorithm is to exclude outliers from the set of pixels that are to be combined in each pixel stack.

  - Combination or the image integration process combines the components of each pixel stack into one pixel of an *integrated image*. There are different methods to improve the signal-to-noise ratio (SNR) using different pixel combination operations.

- There are a variety of means for combining subframes into a final exposure, and each has advantages: The following were discussed.

  - Mean or Average Combine
  - Median Combine
  - Sigma Clip Combine

Summary (continued)

Estimating Exposure Times and Number of Subs

- Hopefully with the previous discussion this summary should be obvious.
- There are a series of constraints on defining the exposure time and number of subs in capturing an image.
  - Equipment capability to produce long exposure times (budget)
  - Patience & time, including sub keep percentage and diminishing returns
  - Signal rejection and combination
  - Uniform Background
  - SNR
  - Noise reduction by stacking
  - Image saturation

Assumed signals

target 27e-/min, background 40 e-/min and DC noise of 0.2 e-/min

Based on 5% SNR diminishing returns for the combination of subs and exposure time; 20 subs and 21 min exposure time. Based on a read noise of 9.3e-, 5% Read noise contribution and background of 40e-/min, the uniform background exposure was about 22 min. Noise reduction by stacking suggested 16 subs or greater. Signal rejection and combination allowed many options but best was a rejection algorithm that required 15 or more subs.

Summary (continued)

Estimating Exposure Times and Number of Subs (continued)

At a first cut all the constraints have created a narrow selections of exposure times and number of subs.

- 16-20 subs and 22 min exposure which creates a total exposure time of 352-440min or 5.9hrs -7.3hrs per filter.

- Assuming shooting LRGB that makes the total exposure time of 23.6-29.2 hrs per subject

That will task the patience and available time!!!

So what can be done to reduce this time?

Actually nothing unless willing to compromise on the performance or your budget!

One thing that could be done is choose a 10% diminishing return on SNR and accept a higher read noise percentage, that would reduce the time allotment by about 50%.

OR

Choose another rejection algorithm that reduces number of subs to 6-8 and accept higher noise/outliers would also reduce the time allotment by about 50%

Now we are getting somewhere on reducing total exposure time!

Is there anything else that can be done?
Yes, and that leads into the next section.

Summary (continued)

Image Capture Strategies

	Image Capture Strategy Options - Summary (case 1)														
Parameter	**Reference**	**1a. Color**	**1b. RGB**	**2a. Bkgrd limited (Bin 1)**	**2b. Bkgrd limited (RGB Bin 2)**	**3a. SNR Dim. Returns (10%)**	**3a. SNR Dim. Returns (5%)**	**4a. Equal RGB/L exp (Bin 1)**	**4b. Equal RGB/L exp**	**5a. Equal RGB/L SNR (Bin 1)**	**5b. Equal RGB/L SNR (Bin 1)**	**5c. Equal RGB/L SNR (RGB Bin 2)**	**5d. Equal RGB/L SNR (RGB Bin 2)**	**7a. RGB/L SNR ratio (RGB Bin 2)**	**7b. RGB/L SNR ratio (RGB Bin 2)**
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RGB	B1 16x10m	B1 16x10m (2-3x)	B1 16x10m	B1 16x66m	B2 16x33m	B1 10x12m	B1 20x22m	B1 16x10m	B2 16x10m	B1 16x13m	B1 16x10m	B2 16x3.3m	B2 16x10m	B2 8x5m	B2 8x5m
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RGB SNR	48	NA	48	153	222	43	90	48	116	58	48	58	116	54	54
RGB/L SNR ratio	0.83	NA	NA	1.7	2.4	0.84	0.88	0.83	2.0	1.0	1.0	1.0	1.0	0.93	0.66
Total Exp Time ratio	1.0	0.5-0.75	0.75	5.5	3.0	0.8	2.75	1.0	1.0	1.24	0.93	0.5	1.6	0.44	0.69
Total Exp Time (min)	640	320-480	480	**X** 3520	**X** 1936	480	**X** 1760	640	640	**X** 794	597	320	**X** 1024	280	440

- The goal of this section was to determine if total exposure time could be reduced and still achieve good color and/or good detail. Above is the Case 1 summary of everything discussed in this section. The options that do not reduce total exposure time are shown with a X. The remaining options cover almost the entire gambit of image capture strategies.
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  - If you believe that L SNR should be above RGB SNR, then consider option 7b.
  - If option 7b is considered to be low in color than consider options 5c and 7a and save in total exposure time at the same time.
  - If options 5c and 7a is consider to still be low in color than start increasing the RGB exposure and/or subs until satisfied. These two options have a lot of total exposure time to trade for color.

Summary (continued)

Image Capture Strategies (continued)

- A lot of discussion has been presented on how to reduce total exposure time by trading the BIN 2 RGB SNR. However, to be fair, the BIN 1 RGB exposure and/or subs could also be reduced to save total exposure time. However doing this will reduce RGB SNR to low values that may be unacceptable.

- Even though it is apparent in the benefits of RGB BIN 2, there are conditions when RGB BIN should not be used. Such as 1) a camera manufacture limiting BIN 2 by more than 50%, 2) objects (i.e. globular clusters) that require full resolution, 3) really good seeing , or 4) color cameras.

- With the selection of an Image Capture Strategy, there are a lot of boundary conditions that have to balanced to achieve an image with great detail and color that satisfy your mind’s eye.
  - Limited Sky Background
  - Noise reduction with stacking
  - Image subs combination algorithms with minimum number of subs
  - Sub keep percentage defined by equipment, and patience which includes amount of acceptable number of sub reshoots due to unwanted artifacts.

Summary

Resolution

- BIN 2 reduces the image resolution by a factor of 2.
- Without increasing telescope focal length while using BIN 2, the image will be undersampled. So native resolution is reduced by 2 and the image may be undersampled too. There is an algorithm developed to improve undersampled images(drizzle), but it is only an improvement, it can’t reproduce the image back to the exact original.
- Seeing conditions and the image scale define the amount of resolution actually lost while using BIN 2.
    - The effect of using BIN 2 does not automatically dictate that the actual observed resolution is cut in half.

Summary (continued)

Example

- To conclude the Summary, an example with three conditions will be provided.
  - Target = 30e-/min,
  - Sky background case 1) 40 e-/min, case 2) 80e-/min, case 3) 160e-/min
  - DC = 1 e-/min, Read noise= 9.3e-
- Minimum number of subs to stack
  - Improving noise estimate by stacking, choose either 8(0.35x) subs, 16(0.25x) subs, or 32 subs(0.18x)
  - PixInsight rejection "Winsorized sigma clipping" algorithms suggests using 15 or greater subs, although other algorithms are available for 3-6, or 10 or more subs.
  - Let's choose 16 subs as provides good noise estimate reduction and rejection of outliers.

Summary (continued)

Example (continued)

- Sky Limited background at 5%
  - Bin 1: Case 1) 22.3 min, case 2) 10.8 min, case 3) 5.4 min
  - RGB Bin 1: Case 1) 75.6 min, case 2) 34.4 min, case 3) 16.5 min
  - RGB Bin 2: Case 1) 16.5 min, case 2) 8.1 min, case 3) 4 min

- SNR diminishing returns
  - Subs
    - Δ % SNR = 5% - 10 subs , Δ % SNR = 2.5% - 20 subs
  - Exposure

	Δ % SNR = 5%	Δ % SNR=2.5%
• Case 1)	11.0m	21.1m
• Case 2)	10.7m	20.7m
• Case 3)	10.4m	20.4m

  - Combined subs/exposure SNR

Δ % SNR = 10%	Δ % SNR=5%
• Case 1) 10x11.0m, total exposure=110m	20x21.1m total exposure=422m
• Case 2) 10x10.7m, total exposure=107m	20x20.7m total exposure=414m
• Case 3) 10x10.4m, total exposure=104m	20x20.4m total exposure=408m

    - Choose Δ % SNR = 10% to reduce total exposure time

Summary (continued)

Example (continued)

- SNR diminishing returns (continued)
  - Assumed Sub Keep percentage max exposure time = 10 m
    Diminishing returns
    - With 10m exposure Δ % $SNR_{Exposure}$ = 5%
    - With 16 subs the Δ % SNR_{Subs} = 3%
    - Combined subs/exposure Δ % SNR=8%
    - Total exposure per filter = 160m, or for LRGB = 640m
  - Sky limited Background with 10m exposure
    - BIN 1: sky background = 160e-/min, Read noise must be 12.7e-
      sky background = 80e-/min, Read noise must be 8.9e-
      sky background = 40e-/min, Read noise must be 6.2e-
    - RGB BIN 1: sky background = 160e-/min, Read noise must be 7.2e-
      sky background = 80e-/min, Read noise must be 5e-
      sky background = 40e-/min, Read noise must be 3.3e-
    - RGB BIN 2: sky background = 4*80e-/min, Read noise can be 18e-
      sky background = 4*40e-/min, Read noise can be 12.7e-

With the assumed read noise=9.3, using BIN 1 the sky background can not be background limited, but RGB BIN 2 can be sky background limited.

Summary (continued)

Example (continued)

- SNR
  - Assume Target = 30e-/min

	SKY Background (e-/min)		
	40	80	160
L SNR =	43	35	27
BIN 1 RGB SNR=	38	32	25
BIN 2 RGB SNR =	84	69	53
BIN 1 RGB/L SNR ratio	0.88	0.91	0.93
BIN 2 RGB/L SNR ratio	1.95	1.97	1.96

  - BIN 2 RGB SNR can be traded to reduce total exposure time or reduce RGB/L SNR ratio to improve detail by using Luminance(L). As a general constraint don't decrease BIN 2 RGB SNR below BIN 1 RGB SNR
  - Previous best options to trade BIN 2 RGB SNR to reduce total exposure time
    - Reduce BIN 2 RGB exposure by 2 or 4
    - Reduce BIN 2 RGB exposure and subs by 2
    - Increase L subs by 2 (remember already assumed at max exposure time)

Summary (continued)

Example (continued)

- Computing RGB/L SNR ratios and total exposure
  - Assume Sky background = 40 e-/min (other values give similar results)
    - BIN 1 RGB/L SNR @ 16x10m = 38/43, TE=640, RGB/L SNR ratio=0.85
    - BIN 2 RGB SNR @ 16x2.5m = 38, TE=280, RGB/L SNR ratio=0.88
    - BIN 2 RGB SNR @ 16x5m = 57, TE=400, RGB/L SNR ratio=1.3
    - BIN 2 RGB SNR @ 8x5m = 41, TE=280, RGB/L SNR ratio=0.95
    - L SNR @ 32 subs = 61, BIN 2 RGB SNR @ 5m/ 8 subs = 41, TE=440, RGB/L SNR ratio=0.67

    - The above options cover RGB/L SNR ratio from 0.67 to 1.3 which were similar to the majority of the ranges obtained from the imager's image capture survey

    - Remember at 16x10m the SNR diminishing returns was increasing at 8% per sub and exposure minute. At 8x5m, each extra sub or minute increases SNR by about 17%. So adding an extra sub and an extra minute substantially increases SNR with only an extra 14 minutes of total RGB exposure time.

Summary (continued)

Example (continued)

- BIN 2 RGB resolution
  - Assume Seeing = 2 arc-sec, pixel size= 5.4microns, focal length=1700mm,
    - BIN 1 Image scale = 0.66 arc-sec/pixel

	Nyquist (BIN 1)			Nyquist (BIN 2)		
	2.5	2.9	3.3	2.5	2.9	3.3
Focal Length	1181	1370	1558	2134	2476	2817

- With the assumed seeing and scope, Nyquist is met with BIN 1 , but not with BIN 2
  - Therefore using BIN 2 RGB, the image will be undersampled with a Nyquist of 1.53.
  - With BIN 2 RGB, the spot size diameter will be larger by 13.4%
  - Resolution loss will be the combination of both.

Conclusions

- This presentation attempted and hopefully succeeded to answer all of the intended objectives.
- Defined the boundary conditions and sensitivity of each to select an image capture strategy with/without Binning
  - Minimum number of subs to reject outliers and improve noise estimation
  - Maximum exposure time to meet user's sub keep percentage
  - Minimum exposure time/subs to keep BIN 2 RGB SNR above BIN 1 RGB value
  - Read noise to meet sky limited background
  - Focal length/image scale to meet seeing conditions, and Nyquist
  - Maximum exposure time/subs to obtain SNR diminishing returns
  - Aperture/focal ratio and seeing to define resolution effects with Binning
- The most difficult boundary condition is meeting the Bin 1 RGB and L sky limited background in a dark sky with 10m exposure and read noise percentage at 5% unless read noise <4e-. At 20m exposures, read noise <4.7e-.
- RGB BIN 2 is easier to achieve sky limited background than with BIN 1.
- RGB Bin 1 has about 1.13x more noise than L and RGB Bin 2 has about 2x more noise than L with equal subs and exposure time.

Conclusions (continued)

- The increased RGB SNR due to BIN 2 can be used to reduce total exposure time at expense of raw color.
- Depending on seeing, aperture, image scale and tracking, BIN 2 RGB may not reduce resolution over BIN 1 RGB
- Even though it is apparent in the benefits of RGB BIN 2, there are conditions when RGB BIN should not be used. Such as 1) a camera manufacture limiting BIN 2 by more than 50%, 2) objects (i.e. globular clusters) that require full resolution, 3) really good seeing, or 4) color cameras
- Color camera can be used to reduce total exposure time 25-50% with loss of resolution and SNR instead of shooting LRGB
- Shooting only monochrome with RGB filters will save 25% total exposure time over shooting LRGB
- SNR is still increasing at over 8% per sub and min at 16x10m and 17% per sub and min at 8x5min. SNR is not near diminishing returns of, for example < 5%.
- The selection of an Image capture strategy is dependent on the user's objective. It can be scientific or a pretty picture or somewhere in between. Scientific can be shooting only Luminance to get the largest SNR the fastest to capture the most detail. But using color to get a pretty picture is user dependent as to the users definition of a pretty picture.

Conclusions (continued)

- The definitive answer to BIN or not is again a user choice as to achieve the desired effect in a satisfactory allowed time period with available equipment.
  - The most obvious reason to BIN 2 RGB is to reduce total exposure time below about 10.5 hours an image (using BIN 1 16x10m as a reference)
    - Regrets
      - More noise with RGB BIN 2
      - RGB BIN 2 resolution loss (depending on seeing and image scale can be minor)
      - Without reducing exposure time or subs, RGB BIN 2 SNR will be about twice Luminance SNR (in this case begs the question…why is luminance being shot?)
      - Manufacturers may limit maximum BIN 2 signal so may not get predicted savings
    - Benefits
      - With reducing RGB BIN 2 exposure time/subs, can reduce total exposure time to less than half.
      - Sky limited background is easier to achieve
      - Can dial in the amount of color desired

Conclusions (continued)

- Using BIN 2 RGB;
  - Without increasing telescope focal length, image will be undersampled by about 2 (assuming BIN 1 RGB met Nyquist between 2.5 and 3.3). Depending on the seeing condition, aperture and image scale, resolution may be worse up to another factor of two.
  - BIN 2 RGB will have about twice the noise of Luminance
    - Increasing the number to subs to improve the noise, only makes the next bulleted statement worse.
  - BIN 2 RGB will have about twice the SNR of Luminance which will reduce the detail achieved by shooting Luminance at Bin 1.

- Generally the first two bullets will have to be accepted as regrets.
  - However, the third bullet can be mitigated by reducing BIN 2 RGB exposure time or number of subs.
    - This provides numerous options to trade BIN 2 RGB SNR for reduced total exposure time, increased Luminance SNR to capture more detail, and dialing-in the desired color while maintaining BIN 2 RGB SNR above the BIN 1 RGB SNR.
    - However, the price of having these options is the limited sky background may become unobtainable without a camera with lower read noise (i.e. <9e-) in a dark sky.

Conclusions (continued)

- In closing, BIN 2 RGB provides numerous options to dial-in RGB and Luminance SNR, RGB/L SNR ratio, total exposure time and color. However there is a price to be paid that requires a compromise with added noise and decreased resolution. Only the user can decided if the added options outweigh the price.

  - There is also an opinion that all this analysis is great, but it's the image processing that make a pretty picture.
  - While it is true that a noisy, color less image can be made to look great by processing….you can do anything in Photoshop….the better the starting image, the easier it is to process and the less image manipulation has to be preformed.
  - Besides knowing what is behind the image capture curtain may allow the image to be captured in less time with more color or more detail then with the current image capture strategy.

- The majority of information in this presentation is to try to optimize your time to get a great image. However, it can't be emphasized enough that to get the best image requires right equipment in a dark sky. This fact is best represented by the planetary images by Damian Peach at http://www.damianpeach.com. His raw images are better than the majority of those after processing.