CCD reductions techniques

Origin of noise

Noise: whatever phenomena that increase the uncertainty or error of a signal

Origin of noises:

1. Poisson fluctuation in counting photons (shot noise)
2. Pixel-pixel gain variation
3. Cosmic Rays
4. CCD readout noise ($RO\left(e^{-}\right)$)
5. Charge transfer efficiency and trailing
6. Wrong reduction algorithms

IMPORTANT: before applying any reduction techniques to treat data, we need to identify the exact sources of the noise affecting the signal. This implies knowing how the observing instruments and the various detectors work and recognizing deviant behaviors from a normal one

Reduction algorithm: the different steps that must be applied to minimize the level of noises affecting a signal, and the methods to retrieve maximum information from the data

The main reduction steps are:
1. Applying mathematical algorithms to eliminate noises on pixel to pixel basis
2. Calibrating the signal (relating analog data to absolute energy)
3. Interpreting the information (ex. applying different filters to get special type of information)

How to reduce data taken with a CCD

The best way to reduce noise is at the source, during observation

- Use the best CCD available -- linearity, high CTE, perfect esthetics (no bad pixel, lines or columns), no dark current, low readout noise;
- Use CCD and settings that are optimized for the type of observation – filters, varying GAIN, binning, using good exposure time

IMPORTANT: experimenting with a CCD during observation; making sure that we understand what the “NORMAL” behavior is; taking all the calibration observations NECESSARY

Each reduction step applied after observation increases uncertainties ⇒ apply only the NECESSARY steps

GOLDEN RULE: the application of a reduction algorithm is legitimate only if it increases the S/N significantly otherwise it is superfluous or damaging

CCD most common noises

Poisson noise

A CCD can be seen as a sort of photon counting device, because the signal registered is (mostly) proportional to the number of photons collected

The basic uncertainty is the one related to ***Poisson noise***. This is the uncertainties related to counting low number of photons. For example, if the mean number of photons detected is X, the uncertainties on the count is the Poisson noise $\sqrt{X}$

Here it is assumed that the fluctuation (rms) in the case of a measured value, x_i, repeated N times, is equal to:

$$rms(x_i) = \left(\frac{\sum_{i=1}^{N} (x_i - X)^2}{N} \right)^{1/2}$$

Example 1:

If the signal detected amount to $X = 10000$ *photons, the Poisson noise related to this signal is* $N = \sqrt{X} = 100$. *The signal to noise ratio is thus equal to* $S/N = X/\sqrt{X} = \sqrt{X} = 100$

NOTE: the Poisson noise is irreducible; the S/N corresponds to the theoretical upper limit; no reducing method can yield a higher S/N.

In reality, to Poisson noise are added other noises of various origin. Before applying any reduction techniques to the data we must determine:

- What phenomenon produce the noise (example Cosmic Rays)
- How does it manifest itself
- Is this noise seriously affecting the data (determining the level of the noise)
- Can it be or should it be corrected
- What algorithms could be applied to minimize it

Overscan and bias

Many CCDs have various extra lines or columns (or both) of pixels which are not exposed. These extra pixels allow estimating the pedestal (BIAS) of an image.

Properly speaking, the OVERSCAN is not a noise. But it needs to be correctly subtracted. Without correcting for the pedestal we cannot talk about Poisson noise.

Example 2:

An overscan of 600 ADU is common. If this was a noise, then with a gain equal to 17 e^{-}*/ADU, which corresponds to 10200* e^{-} */ pixel, the noise would be ~101* e^{-}*. But in reality, the readout noise for such a CCD is only a few* e^{-}

Usually, it suffices to take the mean of the column or line values and subtract it from the image. After correction, the remaining noise should be Poissonian

The overscan can be used to check for potential problems -- for example, an unusually high bias level, could mean that the CCD is heating (means the Deware must be refilled or have some unexpected problems – like a thermal contact)

The overscan can be used also to check for possible structures over the surface of the CCD. In this case it is necessary to subtract a BIAS image (image with zero integration time)

For modern CCD, the bias structure is not an important source of noise. To verify if there is a problem (and if a bias should be used) the following test can be made:

Forming a histogram of the number of pixels versus the counts

1. The distribution of pixel values in a mean bias frame (for which the overscan was subtracted) must have a Gaussian form, with a mean of zero and a width ($FWHM$) defined by the readout noise level RO divided by the square root of the number of co-added frames N_{bias}

$$FWHM \sim \frac{RO}{\sqrt{N_{bias}}}$$

2. Significant deviations from zero for different mean bias suggest significant structures are present

A bias image is obtained by taking a 0 exposure image (the shutter stay closed --- but there must not be any contaminating light). By combining (taking the mean) many bias frames, one obtained a final bias image with high signal and low rms (this usually means taking quite a lot of bias frames). Subtracting the mean BIAS from the image data will get rid of structures in 2D.

Note that in case of an overscan, we subtract a number (the mean value of the pixels in the overscan region), which is equivalent to subtracting a bias image with infinitely low rms

Another advantage of subtracting an overscan is that it also takes into account a possible variation of pedestal level with time

Also, although a bias is a zero time integration image, in reality extra noises add up to the signal during lecture. In particular, DARK noise (if present) may affect the level of the pedestal.

RULES:

- If there are no bias structures, use the overscan
- If a bias image must be use, take the mean of a good number of frames, to reduce the rms (one can take a few ~ 20-30 each night and summed them up at the end of the run). Verify that the structure is stable and is not affected by DARK counts
- One should always take bias frames, even if they are not used after that during reduction

Note that a **preflash** is considered as a bias. If used, the structure produced by the preflash must also be subtracted from the data.

Analog to digital unit (ADU) conversion

The data values of a CCD are Digital Numbers (DN), which are related to the numbers of electrons (or photons detected) by the conversion factor or GAIN: $g\left(e^{-}/ADU\right)$

The counting unit is called **ADU** (**Analog to Digital Unit**)

Although the conversion from an analog signal to a digital one is not a noise, it is important to take this calibration into account before applying any statistical interpretation

- ***In particular, Poison statistic applies to electrons, not ADU***

The readout noise is usually given in electrons, while the associated signal is transformed by the gain factor into ADU. The signal to noise ratio, however, must always be estimated in terms of electrons.

Example 3:

For a signal of X *ADU, the signal to noise ratio (Poisson noise) would be equal to:*

$$S/N = gX/\left(gX\right)^{1/2} = \left(gX\right)^{1/2}$$

For $X = 1000\ ADU$, $g = \left(10e^{-}/ADU\right)$, *this yields a* $S/N = 100$

There is a **discretization error** (round-off error) related to the CCD gain factor. Its value is $g/2$.

This error is related to the way the gain g and the number of bits N_b used to represent the signal are combined in the analog to digital (A/D) converter to yield the maximum electrons representable: $S_{\max} = g2^{N_b}$

Example 4:

For $N_b = 15$ bits *and* $g = 5e^- / ADU$, $S_{\max} = 5\left(e^- / ADU\right) \times 32768 ADU = 163840 \pm 2.5e^-$

Readout noise

Each time a pixel is read by the amplifier, a noise is added to the signal

This is the readout noise, $RO\left(e^-\right)$.

The readout noise is an irreducible noise. We can only minimize it by using CCD with low readout noise (CCD with small pixel sizes) or reducing the number of reading

Modern CCD have very low readout noise varying from a few electrons too a few 10 of electrons

Generally, the gain is chosen (in the lab) in order to resolve the readout noise; for example, with a $RO = 10e^-$ a gain of $g = 5\left(e^- / ADU\right)$ would be natural.

Sometimes, to reach the full well depth for some chips, the gain chosen is larger than the readout noise. The effective readout noise in this case is the quadrature sum of the intrinsic readout noise and $1/2$ the dicretization level.

The readout noise is assumed to be:

1. Independent of position on the CCD
2. Representable as a simple Gaussian error distribution

Example 5:

The S/N ratio of a pixel with X ADU *and readout noise* RO *is:* $S/N = gX / \left(gX + RO^2\right)^{1/2}$

If $g = 10$, $X = 1000$ *and* $RO = 10$, *then* $S/N = 99.5$, *nearly the Poisson limit*

Dark current and Cosmic Rays

The last additive noise is **DARK** current

There are two types of DARK current:

1. A weak signal composed of thermal electrons (a few electrons/hour)
2. Electrons produced by hot pixels

The Dark current is proportional to the exposure time and is function of the CCD temperature

DARK current is detectable by taking a series of different exposure images (usually increasing the exposure time) with shutter closed (must be taken in complete darkness, usually with door of telescope closed). A DARK current appears as an increasing signal with time (usually linear with slope depending on CCD temperature).

If DARK current is present, for each exposure time used during observation one must take various DARK frames with equivalent exposure time. The mean of the DARK is thus subtracted from the image (or a series of DARK with the longest exposure time is taken and subtracted from each image after scaling for proper exposure time)

Taking DARK could be expensive, if long exposure time observations are required

Hot pixels have the same effect as **Cosmic Rays**, except for their persistence (Cosmic Rays are random by nature).

If very few hot pixels are present, make a map of such pixels and do a DARK subtraction (scaled to correct for exposure time) only for these ones

To eliminate Cosmic Rays, one may take the mean of various frames, ignoring any pixels with fluctuations higher than 3 sigmas

Example 6:

The small series 1.0, 1.2, 0.9, 1000.0 and 1.1 has a rms of 399.58, if the deviant pixel is included in the mean estimation. Its value corresponds to a 2.5 sigma deviation only. But excluded in the mean estimation its value represents a 10327 sigma deviation

The problem is that analyzing large matrices of pixel values may be time consuming (although this analysis is now faster using modern PCs)

Taking the median of a group of frames would also take care of most of the random events (but S/N is smaller than for mean)

Saturation

Saturation of the first kind happens when the signal in one pixel goes higher than the full well capacitance allows

On some devices (NIR camera), saturation of first kind could produce **ghost images** that decay away only slowly

Taking bias exposure may help getting rid of these ghost images

Exposure beyond ship saturation may also lead to **charge bleeding** along columns and rows. This usually happens when a faint object of interest is observed at the same time as a very bright star.

The charge trail of a bright star may be kept off from a faint object by rotating the CCD such that the two not align along columns or lines

Gain variation or flatfield reduction

The most important step in the reduction algorithm is the correction for pixel to pixel variation of quantum efficiency. The 2D structure produced by such variation is of low amplitude and consequently very difficult to correct

Theoretically, the necessary calibration is easy to get. It suffices to illuminate the CCD with a uniform light (FLATFIELD). The measured fluctuation is thus related to quantum efficiency variation

In practice there are many problems:
1. Obtaining a really uniformed illumination is usually quite difficult
2. The quantum efficiency depends on the wavelength (color)
3. The flat field is valid only if the distribution of light is the same as for the object

The correction is applied by dividing each image by the normalized flat field.

There are three methods used to make a flat field:
1. A screen attached to the dome is used, illuminated by lamp of quartz (DOME FLAT)
2. The sky at sunset or sunrise is used (SKY FLAT)
3. A part of the sky without stars is used (EMPTY FIELD)

Only method 3 allows obtaining an illumination similar to the observed object. The problem is that fields which are really empty are rare and the exposure time necessary to attain a good S/N may be prohibitive

In methods 1 and 2, high S/N is easily reached, but illumination is rarely homogeneous (DOME FLAT) or equal to the one for the object

Vignetting introduced by the chutter (usually this appears when the exposure time used is comparable to the shutter time reaction) is also considered a quantum variation effect. Since such effect is random, there is no way how to correct it. One should avoid such a problem when observing

Charge transfer efficiency (CTE) and trailing

In modern CCD CTE easily reach 99.995% at low intensity and 99.999% at high intensity

Although the fraction of remaining electrons is low, added together they can be important

Example 7:

For a pixel at the center of a 2048×2048 *CCD, 2048 displacements will be necessary before it is read. Because the CTE is 99.995%, 0.9 or 90% of the electrons will be correctly transferred. This leaves 10% of electrons on the surface of the detector producing some blur*

To check for problem of CTE, it is sufficient to take a long exposure DARK with many Cosmic Rays. The smearing appears as a trailing at the basis of the Cosmic Rays, in the direction of the amplifier.

The trailing is generally more obvious in case of small charges, and the amplitude is proportional to the number of shifts needed for reading the pixel.

This is one problem that can be solved using a PREFLASH. But the price to pay is an increase in readout noise.

Video noise

Two CCD controllers may interact to produce a noise with a frequency similar to the reading frequency. Structures (parallel perpendicular bars) would thus appear

This noise can be due to a poor ground. The solution is electronic (call the technician). Otherwise, the structure may be eliminated using a Fourier filter (at the expense of increasing readout noise)

Reduction algorithm

The different steps in data reduction follow the inverse order of noise introduction

The first steps are additive:

Define one image of i columns and j lines as $DATA^{0}_{i,j}$. The first reduction step consists in subtracting the OVERSCAN (or BIAS) followed, if necessary, by the subtraction of a dark:

$$DATA^{(1)}_{i,j} = DATA^{(0)}_{i,j} - OVERSCAN - (BIAS_{i,j}) - DARK_{i,j}$$

Note that the bias subtraction and dark is not always necessary. The dark is usually scale for the relative exposure time. For precision sake, the correcting images must have rms lower than the RO of the CCD.

The next step is the correction for the GAIN:

$$DATA^{(2)}_{i,j} = \frac{DATA^{(1)}_{i,j}}{FLAT_{i,j}}$$

The flat image is the mean of a high number of FLATFIELD images **normalized to 1**

The last reduction step consists in removing the SKY

$$DATA^{(3)}_{i,j} = DATA^{(2)}_{i,j} - SKY_{i,j}$$

Then follows the calibration steps (transforming ADU to Itensity ($W\ \mathrm{m}^{-2}$) and interpreting the data, applying filters techniques or analysis algorithms