Signal-to-Noise Calculations for IR Imaging

Important Reminder

It is possible to use the new NOAO Exposure Time Calculator to estimate the anticipated time to carry out a particular observation. **However, blind reliance on such a "calculator" without an understanding of the limitations and assumptions can yield misleading results.** This is a brief discussion of what is involved in this exercise.

Calculating Signal and Noise

Using the information in the User's Manual, one can estimate the expected signal for an object of given brightness per unit time, at a given telescope and filter , as well as the statistical noise contribution from the object signal, sky background, dark current, and detector read noise. One may thus estimate the anticipated signal-to-noise (S/N) of a particular observation or, alternatively, the observation time necessary to achieve a desired S/N, which is often a prerequisite for a successful observing proposal. These calculations may be carried out quickly using the exposure time calculator available on the Web, which contains the relevant parameters for both optical and IR imagers at KPNO and CTIO.

This calculation makes two significant assumptions, which must be kept in mind throughout:

- All noise is either independent of the signal (detector read noise) or is the Poisson noise of the total collected signal in electrons.
- All noise sources are statistically independent of each other and may thus be added in quadrature.

Note that it is necessary to always use detected electrons in these calculations. Values given in units such as "ADUs", "counts", "data number", etc. must be converted to electrons using the system gain.

Depending on the brightness of the source, one is generally limited by the photon noise of the source itself or that of the sky background within the detection aperture. The sky background in the IR is sufficiently high (except for narrowband filters at short wavelengths) that detector read noise is rarely a limiting factor in imaging.

If we define the following:

S_t = signal level from a star, integrated over an aperture of **n** pixels, per unit time

S_k = signal level from sky, per pixel, per unit time

R_d = read noise per pixel in rms electrons

N_d = dark current per pixel per unit time

n = number of pixels in detection aperture

T = integration time

Then the S/N is:

$$S/N = S_t / [S_k*n*T + S_t*T + N_d*n*T + R_d^2*n]^{0.5}$$

This formula is that used in the Exposure Time Calculator. Keep in mind the following *caveats*:

- S_k can vary significantly with spatial and temporal variations in the OH airglow in the J and H bands, and with sky temperature in the K band. The shorter cutoff wavelength (2.3 microns) of the K' filter reduces both the background and the effects of thermal fluctuation by comparison to that of the K filter.
- Reduction of IR imaging data requires the subtraction of a background sky frame from each image frame (sky subtraction). If this background frame is obtained as a mean from many individual observations, the additional noise introduced may be small compared to other uncertainties. A worst case is the subtraction of a single sky frame, whose noise increases the S_k*n*T term in the equation above by a factor of 2.
- Note that R_d, since it is already expressed as an rms noise, must be squared before multiplication by the number of pixels. This noise is independent of T. R_d may be reduced, in some instrument systems, by multiple nondestructive reads, but this is likely to be a significant noise source only with narrowband short wavelength filters or in spectroscopy.
- The Exposure Time Calculator estimates the number of pixels **n** from the specified seeing and the pixel size of the detector. This number will almost always be unphysically small and will thus yield optimistic estimates

under the background limited conditions which almost always prevail in IR imaging. Accurate photometry, for example, requires a detection aperture well in excess of the rms seeing size to capture essentially all of the flux despite vagaries in the seeing and telescope tracking. For scientific programs emphasizing point source detection at the expense of photometric precision, **n** may be smaller, but S_t might also have to be reduced by some factor representing the loss of flux in the wings of the image.

In the typical case in which the background sky level is the dominant noise source, note that S/N is proportional to $S_t*T^{0.5}$. If the source brightness doubles, the S/N will double as well, or the same S/N may be obtained in 1/4 the time.

Finally, when using this formula to estimate the amount of telescope time needed, remember to add system overheads for source acquisition, small telescope motions and array readout. The last is the dominant time factor for standard star observations, for example. You may wish to consult with the instrument support scientists for estimates on these factors.

---

rjoyce@noao.edu
16 September 1998