How to recognize the various "flatfield" effects in SNAP data

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Small-scale pixel-to-pixel variations in sensitivity

Variations in the quantum efficiency of a detector from one pixel to its nearest neighbors are sure to occur on SNAP. These small-scale, pixel-to-pixel variations within a single chip are the major component of what is commonly called "flatfielding corrections."

We can determine the corrections easily: take an image using an internal lamp source which illuminates the entire focal plane nearly uniformly. The document Options for Placement of Flatfield Sources (Scholl, 19 May 2004) describes how one might use LEDs for this purpose. A series of lamp exposures will yield very accurately the relative QE on the smallest scales; say, over scales of less than a few tens of pixels (= a few arcseconds). We can then correct the variations in the usual way: divide target images by a normalized version of the flatfield image.

Now, it is surely true that the internal lamp will not illuminate the focal plane uniformly, nor in exactly the same manner as starlight coming through the optics. By using lamp flatfields to correct target images, we will **introduce** systematic errors into the photometry derived from those "corrected" frames. However, the additional "starflat" corrections described below will remove these errors.

One very interesting question is "which lamp(s) should be used for these exposures?" Blue lamps? Red lamps? A mixture of the two? Should different lamp exposures be used to correct images taken with different devices or filters? I do not have the answers to these questions.

Required observations: a series of exposures with the internal lamps.

Intermediate-scale intra-chip variations

A single detector will often have significant large-scale variations in its quantum efficiency. By "large-scale", I mean "over many tens or hundreds of pixels", or "over signficant fractions of its entire extent." In addition to any which are intrinsic to the device, we will add this sort of variation when we divide images by the lamp flatfield images.

We can use "starflats" to identify these errors. The basic idea, as described by Manfroid (1995) or van der Marel (2003), is to take a series of exposures of a starfield, moving the telescope in a grid pattern so that each star is measured at many locations on a single chip. One can fit a model to the variations in observed magnitude as a function of position.

Manfroid states that a 3x3 or 4x4 grid of measurements of a field of 10-20 stars yields excellent results. On the SNAP focal plane, each detector subtends roughly 0.01 square degrees. Using these counts of stars near the SNAP North field, I calculate the following cumulative statistics for number of stars falling on a single detector or filter (the optical CCDs may have 4 filters covering the quadrants of a single chip):

V mag range	stars per chip	stars per filter (1/4 chip)
14.0 - 17.0	7	2
15.0 - 18.0	11	3
16.0 - 19.0	15	4
17.0 - 20.0	22	6
18.0 - 21.0	35	9
19.0 - 22.0	60	15
20.0 - 23.0	89	22

If we require 20 stars per chip (filter) to appear in a typical grid image, this suggests we concentrate on stars in the range from V = 17-20 (20-23). Calculations of the signal-to-noise ratio in SNAP images indicate that a star of magnitude V=20 will have S/N=100 in an exposure of roughly 100 seconds.

To first order, the variations we consider here should not depend strongly on stellar color.

Required observations: a series of exposures while moving the telescope over a grid (say, 4x4 or 5x5 positions) which covers a single chip; another set of grid exposures which move stars over a single filter covering one quadrant of an optical CCD.

Chip-to-chip variations in QE

We can expect each chip to have a slightly different overall quantum efficiency due to variations in the manufacturing process, especially if devices are taken from different lots. As a star moves from one detector of a given sort to another, its observed magnitude will therefore jump by some small amount.

We can determine these variations simply by moving stars from one detector to another of the same sort: that is, from an optical CCD with filter 2 to another optical CCD with filter 2. See factors affecting chip-to-chip offsets for a brief discussion of the effect. Note that this requires both relatively short offsets -- for detectors within the same quadrant of the focal plane -- and large offsets -- for detectors in different quadrants.

To first order, we may treat these corrections as independent of stellar color.

Required observations: a series of exposures while moving the telescope so that stars move from one detector to all the others of the same sort.

Nonuniform exposure times due to shutter

Current designs call for four mechanical shutters near the Cassegrain focus of the telescope. See the Cassegrain Shutter document (Jelinsky 2004). Each shutter would open to allow light to reach one of the four quadrants of the focal plane. As the shutter blade rotates open, it exposes to light the inner portion of the focal plane for a slightly longer time than the outer portion. This leads to exposure times which vary across the focal plane.

Because the shutter blades move quickly (in roughly 50-80 milliseconds), this effect is significant only for short exposure times, less than 10 or 20 seconds. Jelinsky notes that it is possible to design a system to measure the motion of the blades very accurately, to within 1 millisecond, so that one could make accurate corrections with a good optical model. There are two routes one can take here:

A. calculate a correction based on the optical and mechanical design of the telescope. Call this the "theory" option.
B. determine a correction empirically, using exposures with different lengths. Call this the "empirical" option.

Jelinsky (2004) and Lampton (2003, 2004) describe both methods in some detail. It seems reasonable to do both: calculate the expected variation based on the design, and then check it once in orbit.

The effect is largest for short exposures. Consider a 1-second image: my calculations indicate that stars of magnitude V=15 will yield a S/N ratio of 100-300 (highest for red stars measured on the infrared detectors). Most of the stars in the SNAP North field at this magnitude will be of spectral type G and K, which yield S/N approximately 100 in all filters; this corresponds to scatter of about 1 percent from one image to the next. Jelinsky suggests that the size of the shutter effect will be roughly 5 percent for a 1-second exposure. Thus, stars of magnitude V=15 and perhaps a big fainter should show the effect clearly above random noise. Each shutter blade covers a single quadrant of the focal plane, which contains 18 detectors; each detector subtends roughly 0.01 square degrees, so a quadrant samples about 0.18 square degrees. In the magnitude range V=14 to V=17, we expect roughly 130 stars to be detected on each quadrant. This appears sufficient to measure the shutter effect empirically to high precision.

Required observations: a series of exposures with lengths running over a large range; say, 0.5, 1, 2, 3, 5, 10, 20, 50, 100, 200, 300 seconds. The telescope should remain fixed at one pointing during the series; it may also be possible to use a set of images with very small dithers of a few arcseconds for this purpose.

Filter deviations from the design

Although we will provide a clear specification for the SNAP filters, it is possible that small deviations may occur during the manufacturing process. Even if we measure the filters precisely before launch, it is possible that the passbands may shift somewhat after launch, or over the lifetime of the entire mission. How would these changes in effective passband affect the photometry of stars?

We may approximate such deviations from the fiducial passbands as shifts in central wavelength. As shown in this study of passband shifts, there is a clear pattern in the errors such shifts will produce in stellar photometry. The pattern is:

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Type of         As central wavelength of filter shifts
star               blueward                  redward
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 hot blue         grow fainter              grow brighter

 cool red         grow brighter             grow fainter
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The amplitude of these changes is largest in the bluest filters of the optical CCDs and smallest in the infrared filters.

We can look for

a. variations in passband from one instance of a given filter to another of the same filter when the telescope is first launched
b. we can also monitor possible changes over time during the mission.

The key here is to examine differences as a function of stellar color. Differences which do not depend on color may be attributed to chip-to-chip QE variations.

Required observations:

a. a series of exposures while slewing the telescope so that stars move from one device to another with the same filter
b. periodic exposures of the same star field (which will occur automatically in the ordinary "mowing" procedure)

Changes in bandpass due to angle of incidence

If the SNAP filters depend on interference rather than colored glass, there will be significant shifts in the bandpass as a function of the angle with which light strikes the filters. From the inner edge to the outer edge of the focal plane annulus, this angle of incidence varies from about 0.14 to 0.28 radians. How will this affect measurements of stars?

This analysis indicates a simple pattern that should appear as stars move radially away from the center of the focal plane: blue stars grow brighter, and red stars grow fainter. Therefore, one can characterize this effect by taking a series of images and looking at the change in instrumental magnitude as a function of stellar color and distance away from the center of the focal plane.

Required observations: a series of exposures in which stars move (radially) across a single filter, and (radially) from one instance of a filter to another instance of the same filter. Look for changes as a function of stellar color.

Large-scale variations in illumination due to optics

It is possible that the optics may cause small differences in illumination on very large scales across the focal plane; we might call such effects "vignetting." Note that such effects could *not* be detected using images of the internal lamps, since that light does not pass through the optics.

My guess is that any such effects would depend only very weakly on the wavelength of light, and hence only very weakly on stellar color.

I believe that these very large-scale variations would be removed by the application of corrections already mentioned; specifically,

- Intermediate-scale intra-chip variations
- Chip-to-chip variations in QE

Required observations: None.

Summary of observations required to characterize "flatfields"

Going back through the "required observations" sections of this document, I come up with the following list of calibration exposures which help us to determine "flatfield" corrections:

- a series of exposures with the internal lamps
- a series of exposures while moving the telescope over a grid (say, 4x4 or 5x5 positions) which covers a single chip;
- another set of (4x4 or 5x5) grid exposures which move stars over a single filter covering one quadrant of an optical CCD.
- a series of exposures while moving the telescope so that stars move from one detector to all the others of the same sort (both within the same quadrant on focal plane, and across to the other three quadrants)
- a series of images with exposure lengths running over a large range

Note that I have not included as special "calibration" images periodic exposures of the same star field, since these will occur automatically in the ordinary "mowing" procedure.