A simple pipeline for simulating SNAP photometric measurements

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Aug 1, 2004
Aug 19, 2004

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Introduction

I have written code which simulates measurements of stellar magnitudes by the SNAP telescope. It is **not** the official SNAP simulation, nor does it have any relationship to the official software. However, it does allow me to calculate the expected signal from a particular sort of star in a given exposure time, and it also permits me to evaluate various schemes for commissioning the telescope when it first reaches orbit.

Since other SNAP calibration team members may find the program useful, I am making it available to all. This document describes briefly how one can download, install, and use the program.

How to download and install the program

The requirements for running the pipeline are:

- TCL (plus Tk if you want to draw pictures of the focal plane)
- C compiler
- standard Unix tools (e.g., make)
- Perl (to run the selftest script)

Here are very brief instructions for setting things up. I'll follow each step with an example of the procedure.

1. create a directory for the pipeline

```
% cd /data/
% mkdir snap
% cd snap
%
```

2. download the compressed package (a copy should be on my SNAP status page for Aug 19, 2004)

```
% wget http://spiff.rit.edu/richmond/snap/pipeline/aug19_2004/snap_pipeline-0.2.tar.
  100%[====================================>] 6,920,628     36.07M/s    ETA 00:00
  13:47:15 (36.07 MB/s) - `snap_pipeline-0.2.tar.gz' saved [6920628/6920628]
% ls
  snap_pipeline-0.2.tar.gz
%
```

3. un-gzip and un-tar the package

```
% ls
  snap_pipeline-0.2.tar.gz
% tar -xzf snap_pipeline-0.2.tar.gz
% ls
  snap_pipeline-0.2   snap_pipeline-0.2.tar.gz
%
```

4. go into the main source code directory

```
% cd snap_pipeline-0.2
%
```

5. run "./configure"

```
% ./configure
  checking for a BSD-compatible install... /usr/bin/install -c
  checking whether build environment is sane... yes
         (plus lots more like this ...)
  config.status: creating output/Makefile
  config.status: executing depfiles commands
%
```

6. run "make"

```
% make
  Making all in input
  make[1]: Entering directory `/xx/tmp/snap/snap_pipeline-0.2/input'
          (plus lots more like this ....)
  gcc  -g -O2   -o flam_mag  flam_mag.o  -lm
  make[1]: Leaving directory `/xx/tmp/snap/snap_pipeline-0.2'
%
```

7. run "make check"

```
% make check
  selftest.pl: running test of SNAP pipeline code ....
  selftest.pl: about to test for tclsh: ..tclsh ./selftest.tcl..
  selftest.pl: about to test for wish: ..wish ./selftest.tcl..
  selftest.pl: going to use wish as interpreter
```

```
  selftest.pl: cmd is ..wish ./selftest.tcl >& ./selftest.out..
  selftest.pl: about to run SNAP pipeline; this may take a minute ....
  selftest.pl: you may see a graphics window pop up ....
          (and a window may pop up here ....)
  selftest.pl: all tests passed OK
  PASS: selftest.pl
  ==================
  All 1 tests passed
  ==================
  make[2]: Leaving directory `/xx/tmp/snap/snap_pipeline-0.2'
  make[1]: Leaving directory `/xx/tmp/snap/snap_pipeline-0.2'
% 
```

If all goes well, you may see a window with a picture of the SNAP focal plane pop up and then disappear after 10 or 20 seconds. The selftest Perl script should end by writing

```
PASS: selftest.pl
==================
All 1 tests passed
==================
```

to indicate that the pipeline ran a small test procedure successfully. If you now look in the "output" subdirectory, you ought to see a bunch of files created by the selftest script.

If the selftest script fails, you can look in the file "selftest.out" for a log of the pipeline's output as it ran. This may give some clue to any errors which occurred. If you need more information, try editing the file *snap_driver.tcl* to make the "debug" level higher than 2; so, change this:

```
global debug
set debug 2
```

to this:

```
global debug
set debug 6
```

Then run the "selftest.pl" script again:

```
% perl selftest.pl
```

and look once more in the "selftest.out" file for a more verbose log of the pipeline's operations. a value of 6 might be

Once the program has been installed, you should have

- a top-level directory with lots of TCL files
- a sub-directory called "input" with lots of stellar spectra and other input information
- a sub-directory called "output", into which the pipeline places its intermediate and final results
- a sub-directory called "doc" with detailed documentation (including this file)

The file *snap_driver.param* contains a list of "stages":

```
# flags to execute (or not) specific pieces of the pipeline
```

```
#     1       means execute it
#     0       means skip it
do_setup           1
do_refcat          1
do_focal           1
do_filter          1
do_draw_focal      1
do_telescope       1
do_snapshot        1
```

By editing this file and changing the values of some of these parameters to 0, one can skip over portions of the pipeline and save time. For example, by running the "refcat" stage once, one will create a catalog of stars which can be used over and over again for many tests; there is no need to re-create the catalog for each one.

One way to run the pipeline is to start a TCL interpreter and then execute commands from the main program:

```
$ tclsh
% source snap_driver.tcl
```

For convenience, I've created a small text file, "cmd.in", which contains nothing more than this single source command, so that one can execute the pipeline and capture its output in a single command:

```
$ tclsh < cmd.in >& cmd.out
```

Stage 1: setup

The first stage of the pipeline simply modifies the parameter files so that they indicate the proper values for the current installation. The file *setup.param* is an ASCII text file; part of it looks like this:

```
# directory containing the input data: focal plane info, filter
#     transmission curves, star catalogs, etc.
input_dir       ./input
```

The *input_dir* parameter is defined here to have the value "./input", meaning that input files can be found in a subdirectory of the current directory called "input". Many other parameter files contain this same variable *input_dir*.

If you wanted to move the installation so that all the input files were located somewhere else, you might edit the file so that read

```
# directory containing the input data: focal plane info, filter
#     transmission curves, star catalogs, etc.
input_dir       /home/fred/snap/input
```

Since *input_dir* appears in other parameter files, you could edit all of them, too, making the same change in each. However, there is an easier way: when the "setup" stage runs, it takes the values of any parameters in the *setup.param* file and copies their values to all the other parameter files. By changing just one file, *setup.param*, and then running the "setup" stage of the pipeline, any changes

are disseminated to all relevant files.

Stage 2: filters

The second stage of the pipeline prepares the overall transmission curves we will use for each detector on the focal plane. In the *input_dir* are the components which affect the spectral efficiency of the instrument:

- the reflectivity of mirror coatings
- the nominal transmission curves of the fiducial filters
- the quantum efficiency of detectors as a function of wavelength

The "filter" stage of the pipeline convolves these factors in the appropriate way to generate overall transmission curves as a function of wavelength. It places into the *output_dir* two things:

- an "index" which specifies the name and properties of each particular filter/chip combination. In the *filter.param* file, the *filter_assn* parameter gives the name of this index file. Its first few lines might look like this:

```
filt_000 {   0  000A   0   1   5   1 filt_000A.dat }
filt_001 {   1  000B   0   2   3   1 filt_000B.dat }
filt_002 {   2  000C   0   3   4   1 filt_000C.dat }
```

  The zero'th filter lies on quadrant "A" of the chip with index 0. It is based on the fiducial filter with index 5 (the reddest visible filter), but its overall transmission can be found in the file "filt_000A.dat" in the *output_dir*.

- a set of files with names like `filt_000A.dat filt_001B.dat filt_009.dat` which contain the overall passband for each filter/chip combination. Each contains ASCII text like this:

```
8407.0000     0.6792
8408.0000     0.6800
8409.0000     0.6809
```

  in which the first column is the wavelength in Angstroms, and the second column the throughput at that wavelength, on a scale of 0.0 - 1.0.

This stage of the pipeline uses the executable program *spec_convolve* to combine all the individual transmission curves into a single overall curve.

Stage 3: input catalog of stars

The user must supply a set of stars which will be run through the telescope and detectors. This stage of the pipeline converts the input catalog from a format which is relatively easy to provide into one which the code can use.

The input format is based on that of the USNO A2.0 catalog, as provided by SIMBAD's Vizier query facilty. If one visits Vizier and queries this catalog around the position RA=18:00:00 and Dec=+67:00:00, with a search radius of 5 arcminutes, requesting output position in decimal degrees, one will receive a list like so:

```
#Full    _r      _RAJ2000      _DEJ2000    USNO-A2.0       RA(ICRS)    DE(ICRS)
#      arcmin     "h:m:s"       "d:m:s"                       deg         deg
    1  0.4936  269.999675   67.008225  1500-06401275  269.999675   67.008225
    2  0.7868  270.013567   67.011995  1500-06401517  270.013567   67.011995
    3  0.8811  270.030500   67.008584  1500-06401783  270.030500   67.008584
    4  0.9718  270.024300   66.986881  1500-06401699  270.024300   66.986881
    5  1.0931  269.957114   66.992856  1500-06400616  269.957114   66.992856
```

Note that this list includes position (J2000), the B-band magnitude and R-band magnitude. These are (almost) the only pieces used by the pipeline. It uses the (B-R) color to look up and interpolate the spectral type of a star in the file *input_dir/calc_colors.out*. A guess at the V-band magnitude is determined by taking the average of the B and R magnitudes. Using a set of template spectra from Pickles , the pipeline generates synthetic magnitudes for the star in all nine fiducial SNAP passbands. It writes into the *output_dir* a catalog containing the same stars in a somewhat different format, like this:

```
 269.99968   67.00822     f5v  29.278   1 18.050    0 18.309   2 17.931   3 17.8
 270.01357   67.01199     a5v  29.819   1 18.500    0 18.544   2 18.554   3 18.6
 270.03050   67.00858     k0v  24.973   1 13.850    0 14.339   2 13.553   3 13.3
 270.02430   66.98688     f5v  27.628   1 16.400    0 16.659   2 16.281   3 16.2
```

There first element in the list of (filter index, magnitude) has an index of 1; the pipeline assumes that the fiducial SNAP passband number 1 (a slightly redshifted B-band) is close to the Johnson-Cousins V-band, and uses it to normalize magnitudes of stars of different spectral types. That is, it forces an O-star of magnitude V=20 to have the same number of photons in SNAP passband 1 as an M-star of magnitude V=20.

What about light from the sky background? If the user wishes calculations to include the background, he must place into the input catalog of stars a special entry for the sky; my calculations of the background sky brightness indicate that an entry should look like:

```
  9999 sky       271.271281   66.744063    QQ  271.671281   66.744063  23.52  23
```

The RA and Dec, elements 3 and 4, can be modified as desired; it is the magnitude values near the end of this line which are important.

This has special features:

- the second element in the line is the word "sky", which causes the pipeline to use as its spectrum the file *input_dir/uksky.dat*
- the B-band and R-band magnitude values refer, for a sky entry, to the magnitude per square arcsecond in V-band. By making them both 23.52, I am stating that one square arcsecond of the background sky is as bright in the V-band as a star of magnitude V=23.52.

If the input catalog does not contain any "sky" entry, then the calculations of signal and noise will use

a sky value of zero.

Stage 4: the telescope

This stage of the pipeline does very little. It calculates the effective collecting area of the telescope. It also sets the factor by which the telescope optics illuminate one portion of the focal plane differently than another; by default, there is no variation in illumination.

Stage 5: focal plane layout

The SNAP focal plane is a complicated structure: it contains 72 detectors arranged in four quadrants around an annulus. Some of the detectors (the IR ones) have a single filter covering their entire surface, but others (the visible CCDs) are split into four pieces with a different filter in front of each. Moreover, the detectors in each quadrant are rotated relative to each other.

This stage goes through the tedious process of figuring out exactly where on the focal plane each detector lies, how it is rotated, which filters lie in front of it, and so forth. It writes a file into the current directory (not the *output_dir*) indicated by the *foc_output_file* parameter in *focal.param*, which contains a list of all the chips and their properties. This file is then used by other code further downstream.

Note that the parameter file *focal.param* for this stage contains a great deal of information on the layout of the focal plane and properties of the detectors. For example, the lines

```
# default properties of visible CCD detectors
foc_vis_prop { { dark 0.0005 } { read 4  } { gain 2.0 } { sat 130000 } { offset
# default properties of the IR detectors
foc_ir_prop  { { dark 0.04   } { read 20 } { gain 2.0 } { sat 100000 } { offset
```

describe the readout noise, dark current, saturation levels, etc., for the visible and near-IR detectors.

The user can control the cosmetic quality of the detectors via the *foc_chip_variation* parameter. Possible values are

none
: each detector has uniform response across its area

center
: each detector has an identical radial decrease in sensitivity away from its center

linear
: each detector has an identical linear decrease in sensitivity in one direction, uniform response in the other

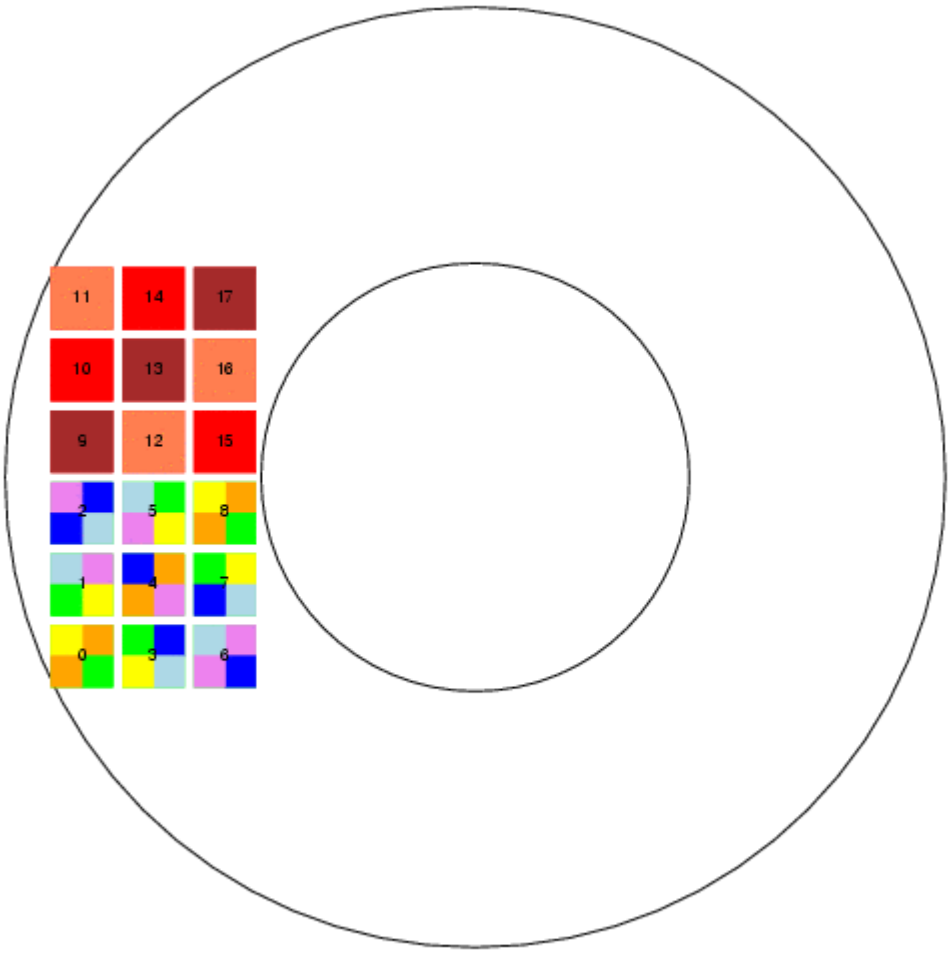
random
: each detector has a different random decrease in sensitivity in an elliptical pattern around a random location on the chip

Any variations are described by a simple polynomial of the form

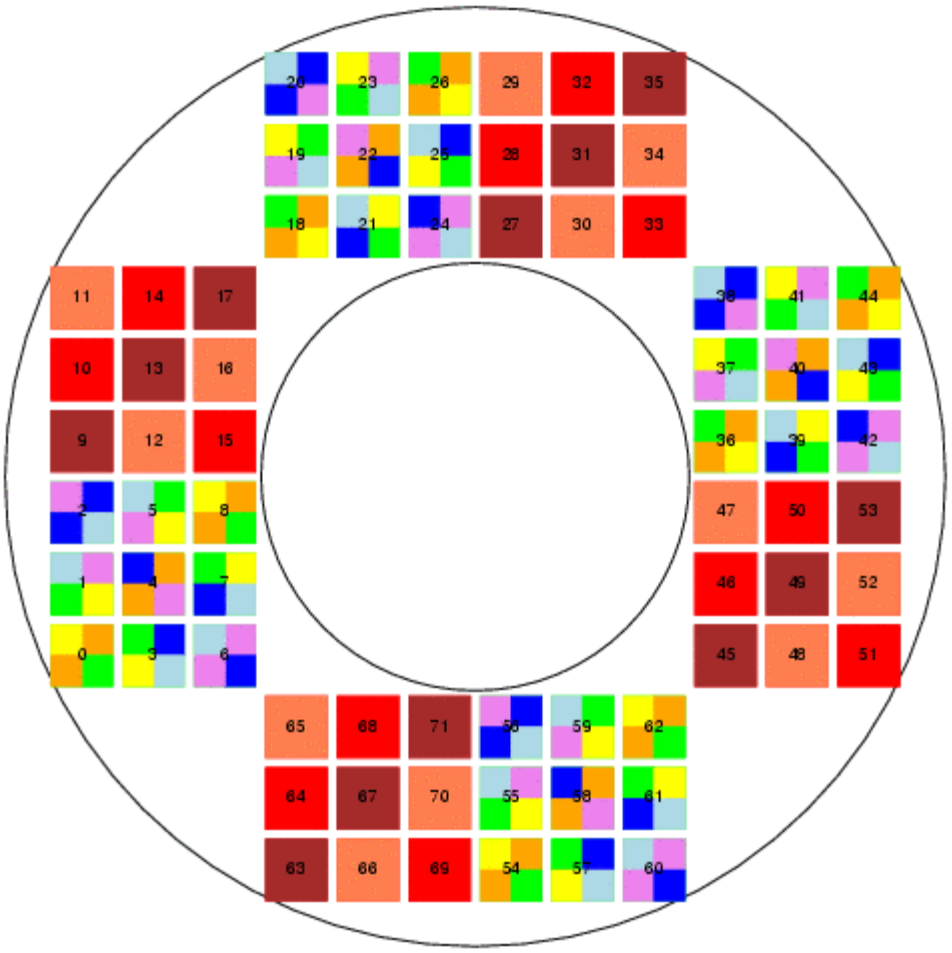
$$\text{relative sensitivity} = \frac{1.0}{a + b*x + c*y + d*x*x + e*x*y + f*y*y}$$

where **x = (row - row0)**, **y = (col - col0)**, and **(row0, col0)** is the location with peak sensitivity. The numerical coefficients of the polynomials describing the variations (if any) will be written into the file indicated by the *foc_output_file* parameter.

The parameter *foc_east_only* in *focal.param* controls whether the detectors are in the East quadrant only (set *foc_east_only* to 1)



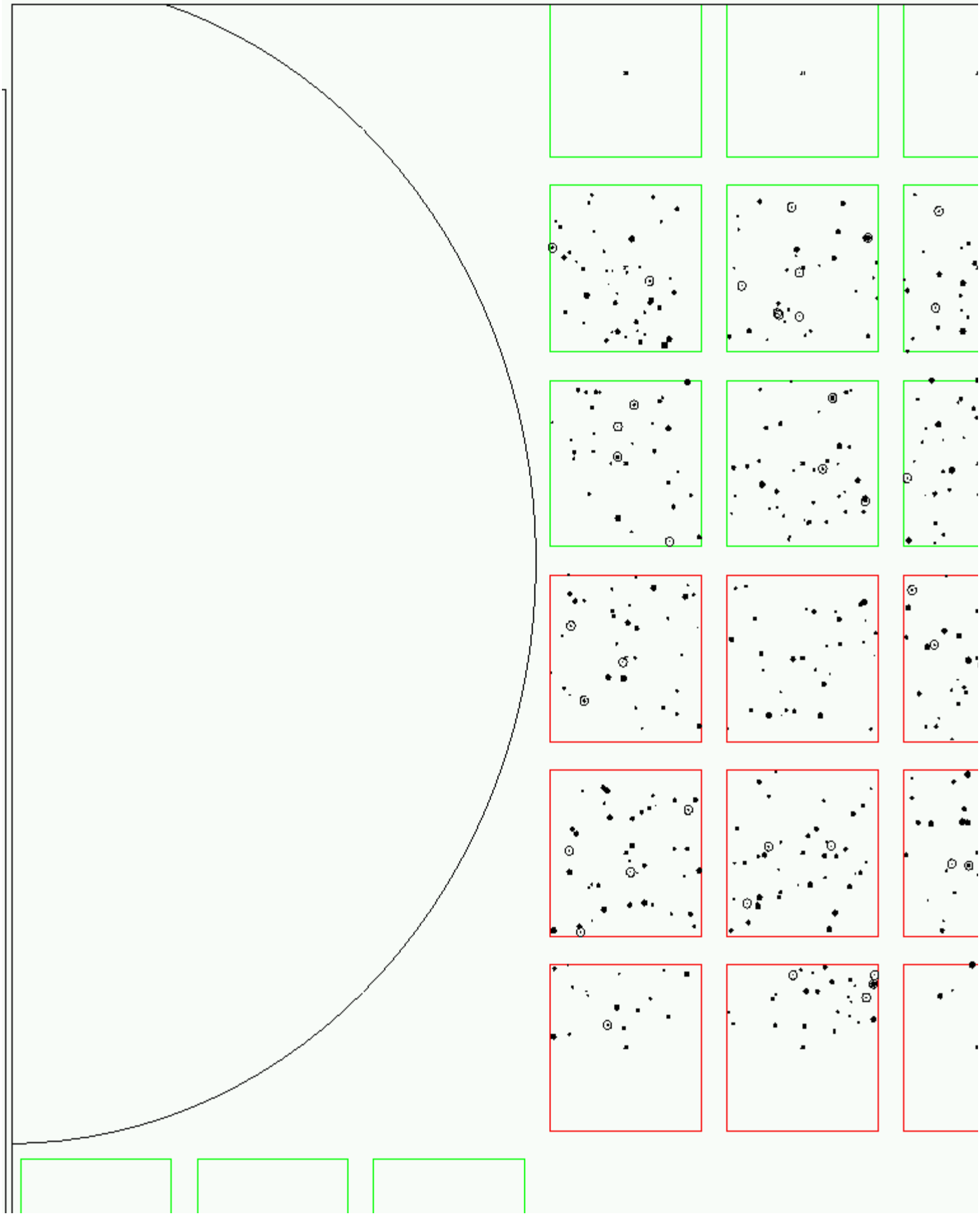
or fill the entire focal plane (set *foc_east_only* to 0)



Stage 6: (optional) drawing the focal plane

If the user chooses to execute the *draw_focal* stage, and if the graphical Tk interpreter is available, then the code will draw a Postscript picture of the focal plane and place it in the *output_dir*. The name of the output file is set by the *output_file* parameter in *focal.param*.

If the user goes on to take a snapshot, then this picture will have placed on it a depiction of all detected stars. As described in my status report of August 21, 2003, the picture uses dots and circles of different sizes to indicate stars of different magnitudes:



Stage 7: taking snapshots

The heart of the pipeline is the calculation of the instrumental magnitude of each star which falls on a detector. Variables in *snapshot.param* allow the user to take one or many "snapshots": each snapshot is a single simultaneous exposure of all the detectors. The parameters

```
snapshot_step_ra            0.0
snapshot_step_dec          -0.01
```

describe how far (in degrees) the telescope moves from one snapshot to the next. At the moment, the user can specify only a single pass of linear motion.

The calculations follow this path:

- determine which detector and filter a given star strikes
- convolve the spectrum of the star with the overall transmission of that filter/detector unit
- normalize the result to photons per square centimeter per second (using Vega as a flux standard)
- calculate the total number of photons detected
- include any vignetting caused by optics
- convert the number of detected photons to an instrumental magnitude

In order to determine the uncertainty in the measurement, we follow the simple model of Howell (1989)

$$S/N = \frac{N_*}{\sqrt{N_* + n_{\rm pix}\,(N_{\rm s} + N_{\rm d} + N_{\rm r}^2)}} \ .$$

We use synthetic aperture photometry, with a circular aperture of size given by the *snapshot_aper_rad* parameter, and assume all the starlight falls within the aperture. We calculate the signal-to-noise ratio for the measurement, and turn that into an uncertainty in magnitude using

$$\text{mag\_uncertainty} = \frac{1.0}{\text{signal\_to\_noise}}$$

If the parameter *snapshot_add_noise* in the *snapshot.param* file is set to 1, then a random value drawn from a gaussian distribution with standard deviation equal to this uncertainty is added to the magnitude measurement. If the *snapshot_add_noise* parameter is zero, then the magnitude is left in its "perfect" state.

The measurements are placed into the *output_dir* in two different files (or sets of files).

- a "terse" version, with name given by the *terse_obsfile* parameter, contains a list of measured stars with RA, Dec, instrumental magnitude and uncertainty:

```
271.27128   66.74406   22.9827   0.0658
271.55585   66.85864   19.4291   0.0079
```

```
271.55585  66.85864  19.9742  0.0104
```

- a "verbose" version, with name given by the *verbose_obsfile* parameter, includes much more information:

```
271.27128  66.74406     sky 34.659  23.908 23.520 23.269 23.079 22.971 23.0
271.55585  66.85864     a0v 31.385  19.955 20.000 20.133 20.292 20.431 20.5
271.55585  66.85864     g0v 31.197  20.346 20.000 19.824 19.707 19.633 19.6
```

The "verbose" output files allow one to search for variations in observed magnitude as a function of position in focal plane, or stellar color, etc. The fields in the verbose output are

1. RA (decimal degrees J2000)
2. Dec (decimal degrees J2000)
3. spectral type
4. magnitude zero point (internal use only)
5. list of magnitude in each of the 9 fiducial passbands (elements 5-13)
14. chip index number
15. row on chip
16. col on chip
17. x-position in the focal plane (mm from center)
18. y-position in the focal plane (mm from center)
19. radial distance from center of focal plane (mm)
20. angle from normal at which light strikes filter (degrees)
21. synthetic magnitude through fiducial filter
22. actual filter index on focal plane
23. fiducial filter index
24. instrumental magnitude
25. uncertainty in instrumental magnitude
26. difference between actual magnitude through telescope and synthetic magnitude through fiducial filter

---

Frequently Asked Questions

1. **How many photons are actually detected in some particular exposure of a given star?**

   The instrumental magnitudes produced by the pipeline have the form

   ```
   mag  =  mag_zero  -  2.5*log10( num_photons )
   ```

   where the value of "mag_zero" is given by the *snapshot_mag_zero* parameter in the *snapshot.param* file; its default value is 30.0. So, for example, if the given star appears in an output file with magnitude 24.65, then the number of detected photons must be

   ```
                          0.4*(mag_zero - mag)
   num_photons  =  10
   ```

$$= 10 \qquad = \frac{0.4*(30 - 24.65)}{0.4*(30 - 24.65)} = 138$$

2. **Is it possible to modify the filter passbands?**

   Yes, but it will take a bit of work. The *input* directory contains a set of files containing the default passbands for the SNAP filters, with names like *fiducial_b0.filter*, *fiducial_b1.filter*, etc. You may either modify by hand the values in these files, or create a different set of files with the same simple 2-column ASCII format; then re-run the *do_filter* step of the pipeline. This should create a new set of overall (filter plus mirrors plus detectors) passband files in the *output* directory with names like *filt_003A.dat*.