Using a free-flying spacecraft to calibrate standard stars (III)

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The basic plan

Send a free-flying spacecraft into low earth orbit (LEO).

Place on board:

- one telescope, for capturing light from stars
- a target which reflects sunlight into the telescope
- one set of detectors: optical CCDs, near-IR array devices.
- plus the usual satellite stuff: communications, power, orientation, etc.

The main advantages of a freeflyer:

- avoids all atmospheric effects
- provides indirect sunlight as a secondary calibration source
- has time to measure many stars
- has time to measure faint stars

Using the Sun as a reference source

There are several instruments which currently (or in the near future) measure the solar irradiance. For example,

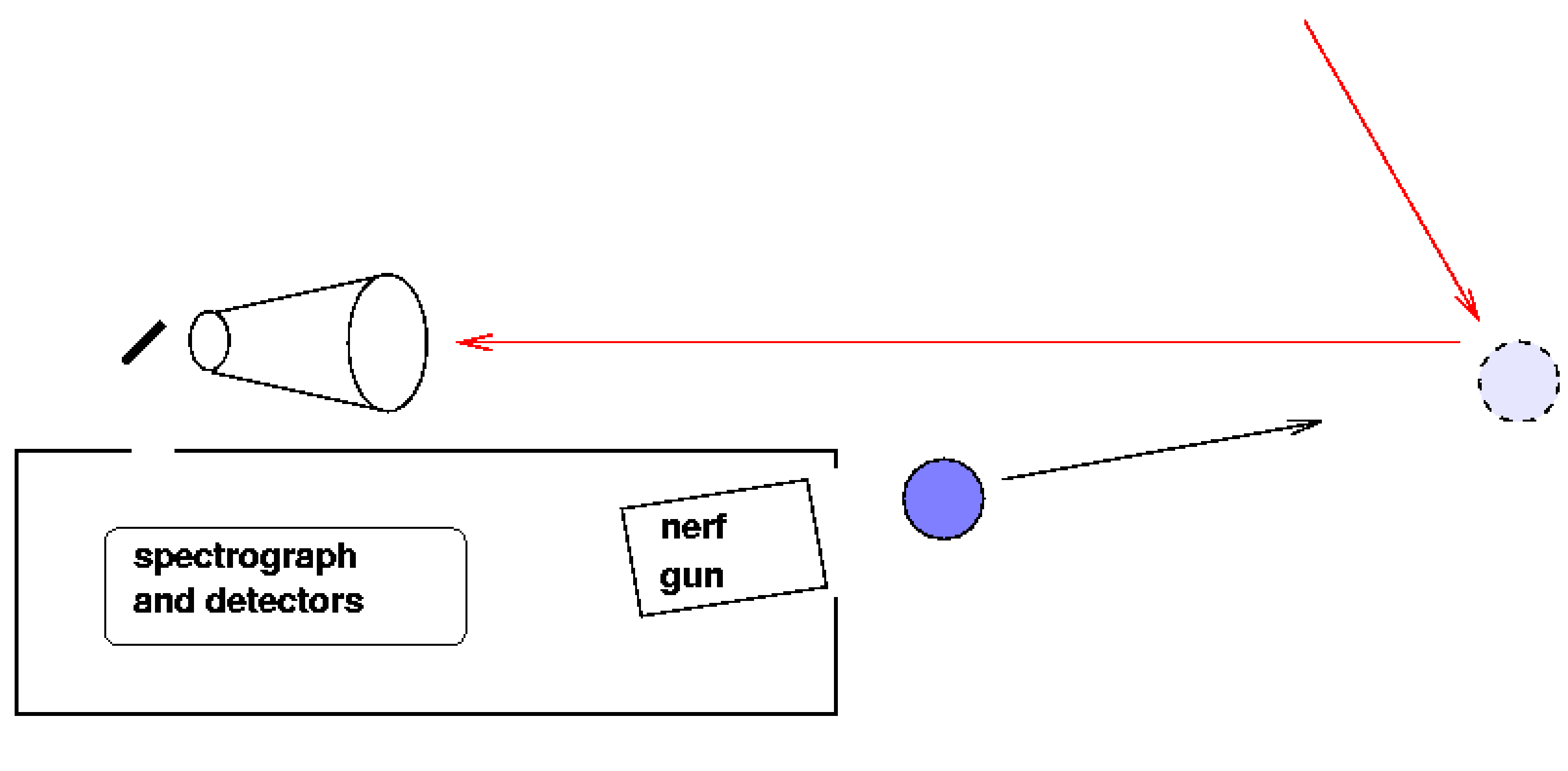
- The ACRIM experiments, one of which is carried on the UARS satellite
- The SOURCE experiment

By using the Sun as a reference source, we let other groups do much of the hard work.

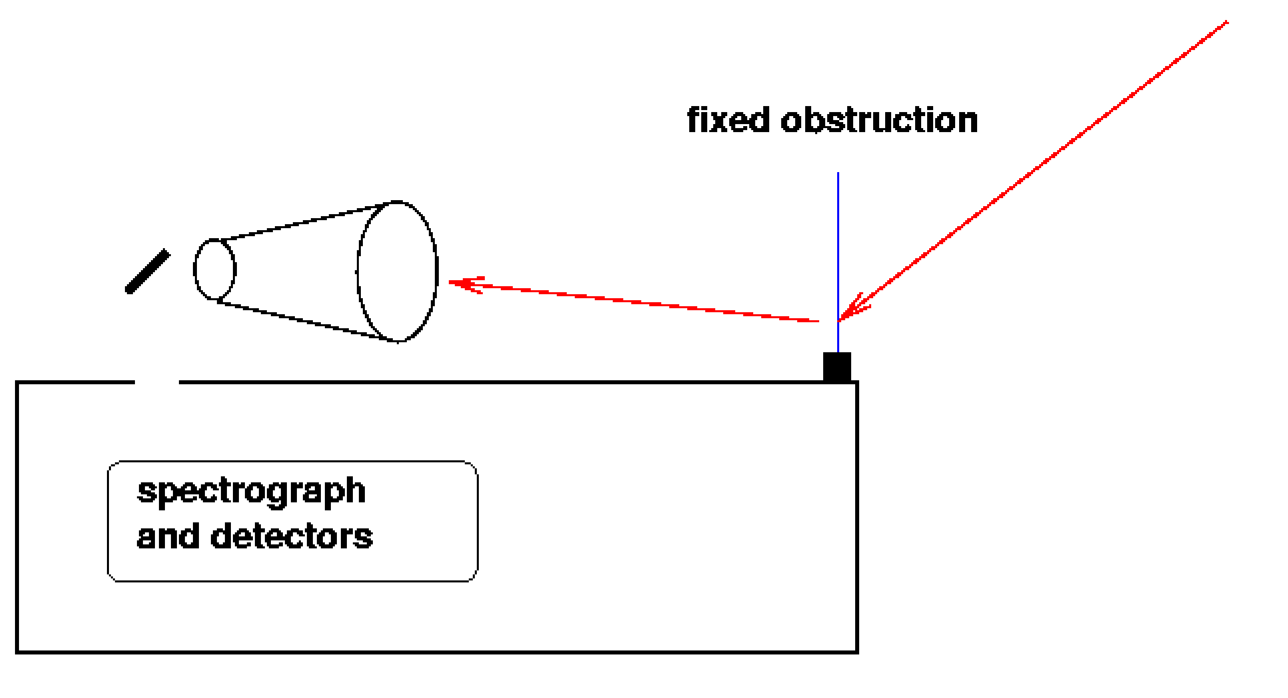
We can, of course, include several on-board sources as additional references, just to verify that the instruments are not suffering significant contamination or degradation. LEDs are a reasonable choice, and the "fixed obstruction" method mentioned below provides a natural way to send light from an LED through the main optics into the detector.

How can we measure sunlight through the very same optical path as starlight? Two options involve reflected sunlight.

1. shoot small balls from the spacecraft out into space, and take pictures as they move away; this technique was used on the MSX satellite: see Price et al., AJ 128, 889, 2004.



2. place a small obstruction within the field of view of the telescope. The obstruction will reflect sunlight into the telescope when illuminated, but negligible amounts of light when the spacecraft is in darkness

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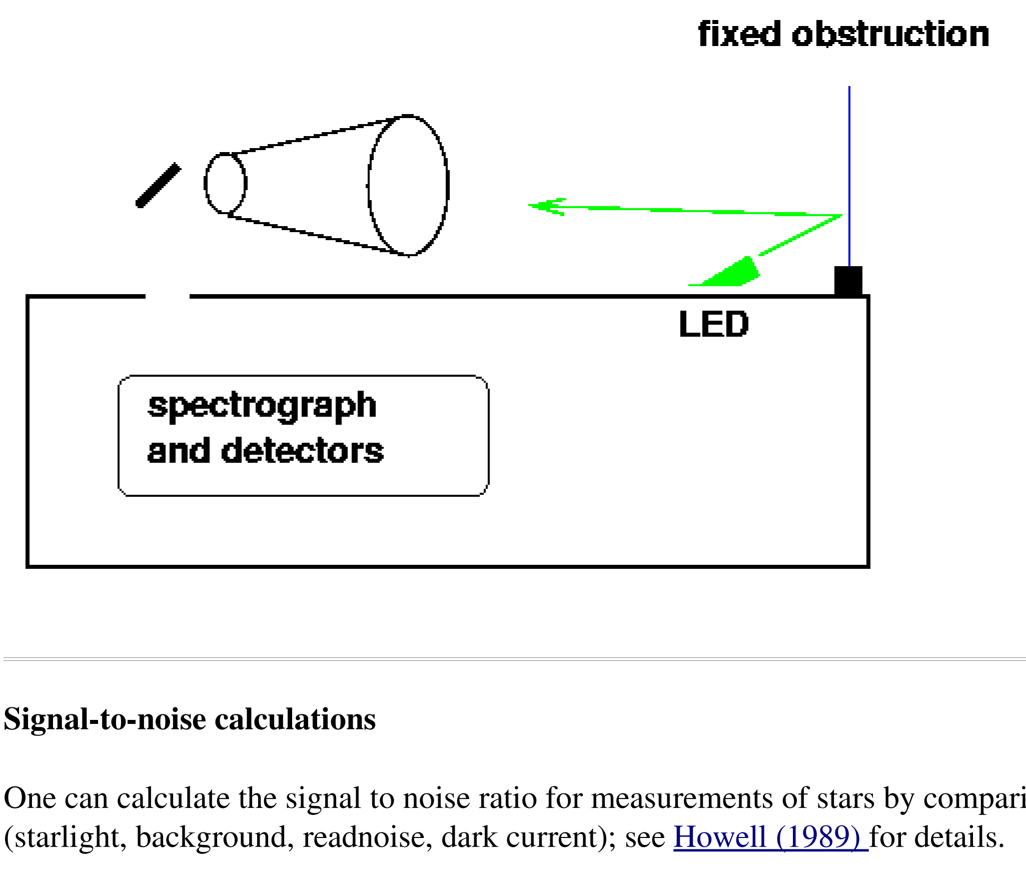
Method                     Pro                          Con
------------------------------------------------------------------------------
shoot "nerf balls"      no effect on ordinary         only a few chances
                          observations                moving parts
                        objects in focus              requires tracking balls
                                                      cannot check reflectance

fixed obstruction       will definitely be            object not in focus
                          recorded                    small effect on ordinary
                                                        observations
                        can check reflectance
------------------------------------------------------------------------------
```

Each method has its advantages and disadvantages.

The analysis of the "nerf ball" method is relatively simple: each ball (eventually) becomes a point source in images and can be compared easily to stars. The analysis of the "obstruction" method is more difficult: since the object will be very far from focus, its light will appear as a diffuse background on images. Nevertheless, as the satellite passes into and out of the Earth's shadow, one can measure the change in this background accurately; it is a matter of geometry and optics to convert the background into an effective solar irradiance.

On the other hand, the logistics of making the measurements favors the fixed obstruction. The MSX experiment fired five spheres away from the satellite, but managed to track only two of those completely as they moved away from the spacecraft. The obstruction is always in the same place, and never has to move. Moreover, one can shine an internal light source onto the obstruction while in the Earth's shadow to check the reflectivity of the obstruction, both as a function of wavelength, and as a function of time on orbit.



Signal-to-noise calculations

One can calculate the signal to noise ratio for measurements of stars by comparing the signal (starlight) to the sources of noise (starlight, background, readnoise, dark current); see Howell (1989) for details.

I made the following assumptions:

- spectrograph resolution R = 1000
- f/20 optical system
- visible CCD detectors identical to current SNAP design
  - pixel size 0.010 mm
  - readnoise 4 electrons
  - dark current 0.0005 electrons per pixel per second
- near-IR detectors identical to current SNAP design
  - pixel size 0.018 mm
  - readnoise 20 electrons
  - dark current 0.04 electrons per pixel per second
- light from a star is spread out over 10 pixels on the detector
- overall QE of optics plus spectrograph plus detectors is 1 percent
- star has spectrum of Vega (Bohlin and Gilliland 2004)
- sky background as determined in an earlier SNAP technical note

The results, in tabular form. Each table shows the overall signal-to-noise ratio per wavelength bin element for a set of exposure times (in seconds) and a set of telescope diameters. There are tables for stellar magnitudes ranging from 0 to 15.

First, measurements in the optical: SNAP filter 1, centered on 515 nm, similar to Johnson V.

```
#   star mag    0
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     7.860e+00   3.474e+01   1.155e+02   3.672e+02   1.162e+03   3.674e+03
D =  10     2.041e+01   7.242e+01   2.320e+02   7.347e+02   2.324e+03   7.348e+03
D =  20     4.484e+01   1.464e+02   4.646e+02   1.470e+03   4.647e+03   1.470e+04
D =  50     1.155e+02   3.672e+02   1.162e+03   3.674e+03   1.162e+04   3.674e+04
D = 100     2.320e+02   7.347e+02   2.324e+03   7.348e+03   2.324e+04   7.348e+04

#   star mag    5
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     1.063e-01   1.025e+00   7.859e+00   3.473e+01   1.155e+02   3.671e+02
D =  10     4.199e-01   3.691e+00   2.041e+01   7.241e+01   2.320e+02   7.347e+02
D =  20     1.603e+00   1.114e+01   4.484e+01   1.464e+02   4.646e+02   1.470e+03
D =  50     7.860e+00   3.474e+01   1.155e+02   3.672e+02   1.162e+03   3.674e+03
D = 100     2.041e+01   7.242e+01   2.320e+02   7.347e+02   2.324e+03   7.348e+03

#   star mag   10
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     1.067e-03   1.067e-02   1.063e-01   1.023e+00   7.794e+00   3.418e+01
D =  10     4.268e-03   4.262e-02   4.198e-01   3.687e+00   2.034e+01   7.209e+01
D =  20     1.706e-02   1.696e-01   1.603e+00   1.113e+01   4.479e+01   1.463e+02
D =  50     1.063e-01   1.025e+00   7.859e+00   3.473e+01   1.155e+02   3.671e+02
D = 100     4.199e-01   3.691e+00   2.041e+01   7.241e+01   2.320e+02   7.347e+02

#   star mag   15
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     1.067e-05   1.067e-04   1.067e-03   1.065e-02   1.047e-01   9.026e-01
D =  10     4.269e-05   4.269e-04   4.267e-03   4.255e-02   4.136e-01   3.322e+00
D =  20     1.707e-04   1.707e-03   1.706e-02   1.693e-01   1.581e+00   1.046e+01
D =  50     1.067e-03   1.067e-02   1.063e-01   1.023e+00   7.794e+00   3.418e+01
D = 100     4.268e-03   4.262e-02   4.198e-01   3.687e+00   2.034e+01   7.209e+01
```

Now, measurements in the near-IR: SNAP filter 7, centered on 1300 nm.

```
#   star mag    0
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     8.195e-01   7.758e+00   5.433e+01   2.200e+02   7.193e+02   2.282e+03
D =  10     3.217e+00   2.675e+01   1.323e+02   4.525e+02   1.443e+03   4.567e+03
D =  20     1.200e+01   7.512e+01   2.822e+02   9.114e+02   2.888e+03   9.136e+03
D =  50     5.434e+01   2.201e+02   7.195e+02   2.283e+03   7.223e+03   2.284e+04
D = 100     1.323e+02   4.525e+02   1.443e+03   4.568e+03   1.445e+04   4.568e+04

#   star mag    5
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     8.248e-03   8.243e-02   8.191e-01   7.724e+00   5.320e+01   2.127e+02
D =  10     3.299e-02   3.291e-01   3.215e+00   2.666e+01   1.313e+02   4.483e+02
D =  20     1.318e-01   1.306e+00   1.200e+01   7.500e+01   2.816e+02   9.093e+02
D =  50     8.195e-01   7.758e+00   5.433e+01   2.200e+02   7.193e+02   2.282e+03
D = 100     3.217e+00   2.675e+01   1.323e+02   4.525e+02   1.443e+03   4.567e+03

#   star mag   10
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     8.249e-05   8.248e-04   8.244e-03   8.203e-02   7.819e-01   5.651e+00
D =  10     3.299e-04   3.299e-03   3.297e-02   3.275e-01   3.074e+00   2.078e+01
D =  20     1.320e-03   1.320e-02   1.318e-01   1.300e+00   1.154e+01   6.528e+01
D =  50     8.248e-03   8.243e-02   8.191e-01   7.724e+00   5.320e+01   2.127e+02
D = 100     3.299e-02   3.291e-01   3.215e+00   2.666e+01   1.313e+02   4.483e+02

#   star mag   15
# exptime=        0.1         1.0        10.0       100.0      1000.0     10000.0
D =   5     8.249e-07   8.248e-06   8.245e-05   8.208e-04   7.864e-03   5.831e-02
D =  10     3.300e-06   3.299e-05   3.298e-04   3.283e-03   3.145e-02   2.330e-01
D =  20     1.320e-05   1.320e-04   1.319e-03   1.313e-02   1.257e-01   9.284e-01
D =  50     8.249e-05   8.248e-04   8.244e-03   8.203e-02   7.819e-01   5.651e+00
D = 100     3.299e-04   3.299e-03   3.297e-02   3.275e-01   3.074e+00   2.078e+01
```

Comparison with other methods

Scientific criteria only:

- Pro
  1. No atmospheric effects
  2. Provides reflected sunlight as a secondary calibration source
  3. Can cover a range of magnitudes
  4. Has time to measure many target stars
- Con
  4. Cannot bring instrument back afterwards to check for changes
  5. (probably) Can't measure same targets as SNAP

Postscript versions of the main illustrations

- Basic spacecraft design
- Using "nerf balls" for reference
- Using a fixed obstruction for reference
- Using LEDs to check reflectance of obstruction