Computing the Sensitivity of Keck Instruments

Gregory D. Wirth
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Background

In June 2009, the Astro2010 Decadal Survey Committee requested that WMKO supply information on the imaging and spectral sensitivity of our instruments. The request specifically states:

```
In order to make entries compatible across wavelength regines, we are
trying to standardize sensitivity as Flux Density (erg/cm2/s/keV; S/N=5 in
1 hour) or Sensitivity (Jy; S/N=5 in 1 hour), so use of those units would
be much appreciated.
```

In most cases these numbers are not well determined for Keck instruments. In this document, we show how to derive such numbers using DEIMOS and ESI as examples.

Spectral Sensitivity

Estimating S/N

The signal-to-noise of a spectroscopic observation can be estimated from first principles by computing the signal and the noise in the observation.

Signal

The signal is the number detected electrons received from the source over the course of an exposure, and can be computed using this formula:

```
Signal = ObjectFlux * ExposureTime
```

where the quanities are as follows:

- **ObjectFlux** is the number of detector photons per unit time from the source, computed as:

  ```
  ObjectFlux = AbsoluteFlux * Dispersion * EffectiveAperture * $
  Efficiency * 10^(-0.4*(ApparentMagnitude + Extinction))
  ```

  [photons/sec].
- **AbsoluteFlux** is the photon flux [photons/sec/AA/cm^2] for an object of apparent magnitude m=0 incident on the top of Earth's atmosphere. It can be computed as described here.
- **Dispersion** is the grating dispersion at the wavelength of interest [Å/px].

- **EffectiveAperture** is the collecting area of the telescope [cm^2].
- **Efficiency** is the fraction of incident photons which are detected, and is thus a product of the detector QE and the throughput of the optical system (including grism or grating) [dimensionless].
- **ApparentMagnitude** is the apparent brightness of the source at the given wavelength [magnitude].
- **Extinction** is the number of magnitudes of extinction due to Earth's atmosphere [magnitude].
- **ExposureTime** is the length of the exposure [sec].

Noise

We consider 3 sources of statistical noise:

- **Object noise:** sqrt(N) photon from the source.
- **Sky noise:** sqrt(N) photon from the background within the slit.
- **Read noise:** noise added by the datataking system.

Although other sources of systematic noise exist (most notably, sky subtraction errors), we ignore them in this idealized approach. The total noise for the observation can be estimated by adding the various noise sources in quadrature:

```
TotalNoise = sqrt( ObjectNoise^2 + SkyNoise^2 + $
                              SubExposures*ReadNoise^2)
```

where quantities are defined as follows:

- **ObjectNoise** computed as `sqrt(Signal)`, where `Signal` was defined above.
- **SkyNoise** computed as `sqrt(SkySignal)`.
- **Readnoise** is the detector read noise [electrons].
- **SkySignal** computed as `SkyFlux * ExposureTime`.
- **SkyFlux** computed via

```
SkyFlux = AbsoluteFlux * Dispersion * SlitArea * EffectiveAperture * $
    Efficiency * 10^(-0.4*SkyMagnitude)
```

- **SlitArea** is the product of the slitwidth and the slit length used to sum the object spectrum [arcsec^2].
- **SkyMagnitude** is the sky brightness, which can be obtained here [mag/arcsec^2].
- **SubExposures** is the number of separate exposures which make up the entire observation, thus increasing the read noise by a factor of `sqrt(SubExposures)`.

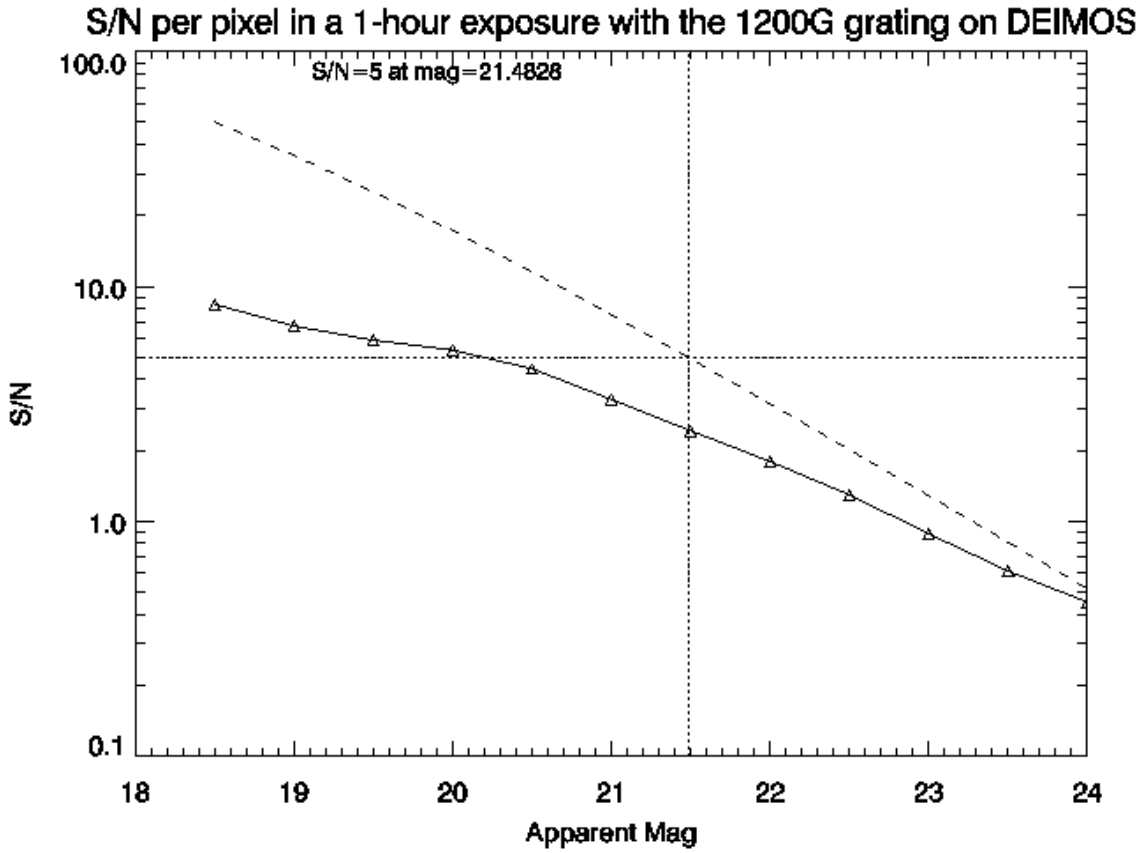
This calculation can be performed using the IDL routine spectral_s2n.pro.

Comparison with Actual DEIMOS S/N

To determine whether the formulas above accurately predict the S/N for DEIMOS, we compare the predicted results to real S/N values provided by the DEEP2 Survey with DEIMOS. For purposes of comparison, we use these parameter values:

- SkyMagnitude = 19.9 (median sky mag/sqarcsec in R from Gemini for lunar age<7d per Gemini website).
- ReadNoise = 2.5 electrons (from DEIMOS web page
- AbsoluteFlux = 620 computed from here.
- Dispersion = 0.33 (for DEIMOS 1200G grating).
- EffectiveAperture = 7.6e5 cm^2 (Keck effective aperture is 76 m^2 per Keck Report #90)
- Extinction = 0.1 (from Gemini website for 7000AA on Mauna Keaa)
- SlitArea = 1.0*2.0 (slitwidth=1.0, slit length=2.0)
- ExposureTime = 3600. (1 hour)
- SubExposures = 3 (3×1200s)
- Efficiency = 0.2 (throughput at 7000AA was 26% when new; assume some degradation plus QE loss)

The computation of S/N as a function of apparent magnitude is performed using the script plot_spectral_s2n_vs_mag_deimos.pro. The figure below compares the predicted S/N (dashed line) against the DEEP2 results (solid line).



The following table shows these results:

ApparentMag	S/N(pred)	S/N(act)	Ratio (pred/act)
18.5	50.2691	8.37000	6.00587
19.0	36.1320	6.77000	5.33707
19.5	25.2973	5.89000	4.29495
20.0	17.2715	5.35000	3.22831
20.5	11.5372	4.45000	2.59264
21.0	7.57398	3.29000	2.30212

```
     21.5      4.90838      2.42000      2.02826
     22.0      3.15210      1.79000      1.76095
     22.5      2.01176      1.29000      1.55951
     23.0      1.27872     0.880000      1.45309
     23.5     0.810624     0.610000      1.32889
     24.0     0.513002     0.450000      1.14000
```

As expected, the predicted S/N values are more optimistic than the actual numbers for real galaxies. The main reason for this is probably slit losses, which are not accounted for in the model (which assumes that all light does down the slit). If slit losses for typical R=21 galaxies are 50%, then the numbers agree well. The fact that brighter galaxies show a greater discrepancy with the predicted values is consistent with brighter galaxies being closer and thus larger in angular size, with correspondingly higher slit losses.

The bottom line is that the predicted S/N numbers agree well with the actual numbers when slit losses are accounted for, and are thus suitable for using in the sensitivity estimates for the Astro2010 spreadsheet.

Estimating Sensitivity

We obtain the sensitivity as follows:

- Locate the apparent magnitude for which the predicted S/N in 3600 sec is 5.
- Convert this magnitude into Jansky via the NICMOS conversion form.

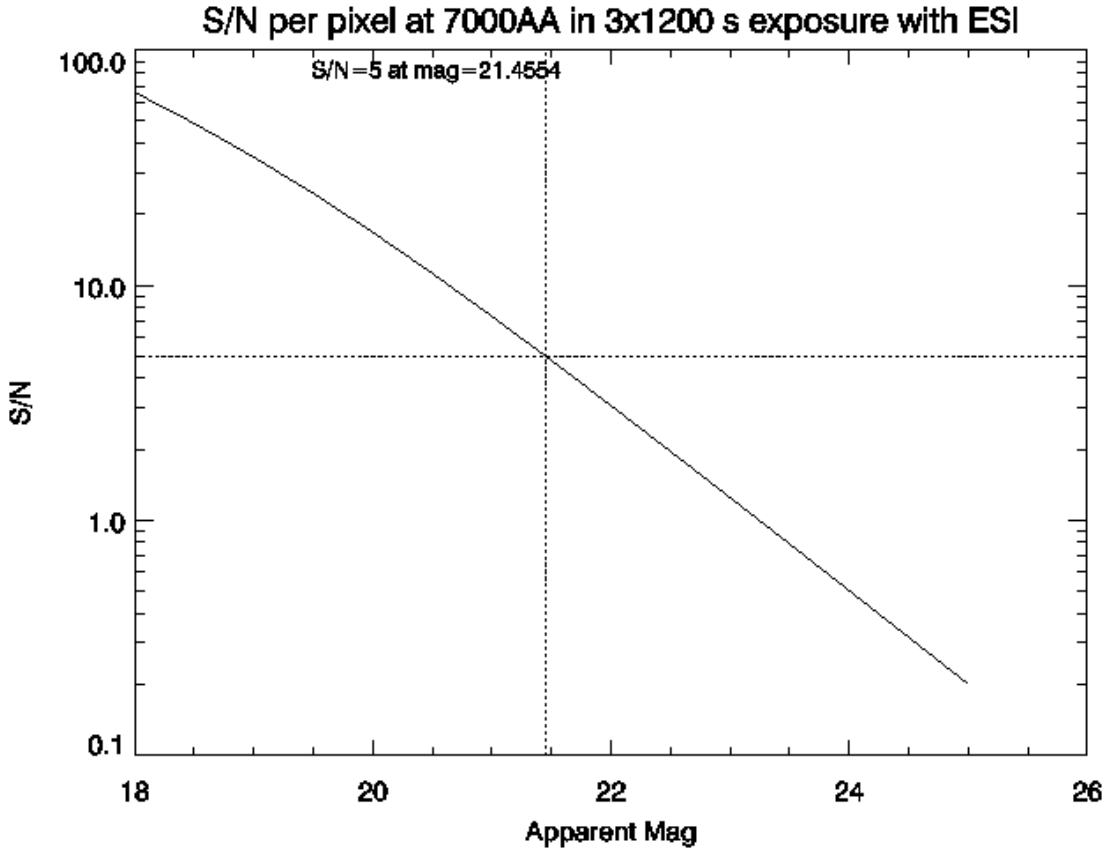
DEIMOS

As indicated by the dotted line in the plot above, the predicted DEIMOS S/N is 5 at R=21.48. Here is the conversion to Jy:

```
 INPUT FROM THE FORM IS
Input units = magnitude R
Output units = Jy
Input flux =    21.4800 magnitude R
Temperature of the blackbody =    5500.00
INPUT wavelength =    0.700000 micron
OUTPUT wavelength =    0.700000 micron
Flux=7.36E-06 Jy
```

ESI

The following plot is generated by the script plot_spectral_s2n_vs_mag_esi.pro.



From the image, the S/N=5 point is 21.45 mag in R, To convert to Jy:

```
INPUT FROM THE FORM IS
Input units = magnitude R
Output units = Jy
Input flux =    21.4500 magnitude R
Temperature of the blackbody =    5500.00
INPUT wavelength =    0.700000 micron
OUTPUT wavelength =    0.700000 micron
Flux=7.57E-06 Jy
```

Summary

Derived sensititivies:

- **DEIMOS:** 7.23E-06 Jy
- **ESI:** 7.57E-06 Jy

Imaging Sensitivity

TBD.

Gregory D. Wirth
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