PHOTOMETRIC CHARACTERISTICS OF DATA FROM THE HUBBLE SPACE TELESCOPE GODDARD-HIGH RESOLUTION SPECTROGRAPH

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ABSTRACT. The G-HRS is one of four axial scientific instruments which will fly aboard the Hubble Space Telescope (ref 1,2). It will produce spectroscopic observations in the 1050 A $\leq \lambda \leq$ 3300 A region with greater spectral, spatial and temporal resolution than has been possible with previous space-based instruments. Five first order diffraction gratings and one Echelle provide three modes of spectroscopic operation with resolving powers of $R = \lambda/\Delta\lambda$ = 2000, 20000 and 90000. Two magnetically focused, pulse-counting digicon detectors, which differ only in the nature of their photocathodes, produce data whose photometric quality is usually determined by statistical noise in the signal (ref 3). Under ideal circumstances the signal to noise ratio increases as the square root of the exposure time. For some observations detector dark count, instrumental scattered light or granularity in the pixel to pixel sensitivity will cause additional noise. The signal to noise ratio of the net spectrum will then depend on several parameters, and will increase more slowly with exposure time. We have analyzed data from the ground based calibration programs, and have developed a theoretical model of the HRS performance (ref 4). Our results allow observing and data reduction strategies to be optimized when factors other than photon statistics influence the photometric quality of the data.

1. THE ANALYTICAL MODEL

Counts are collected into spectrum "bins" and background "bins". The spectrum bins measure the gross signal of spectrum + background + dark count. The background bins measure background + dark count. There are three sources of noise; photon noise in the spectrum bins, photon noise in the background bins, and fluctuations in the spectrum counts due to granularity. If the noise sources are random and independent of each other their variances should add.

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 35–38.

Let: S = signal count rate - counts per diode per second - product of stellar flux and G-HRS sensitivity (ref 2)
bS = scattered light background count rate
b = background fraction relative to the adjacent spectrum
d = detector dark count rate - counts per diode per second
t = total observing time - seconds
f = fraction of time spent measuring the spectrum
ft = spectrum exposure time - seconds
$(1-f)t$ = background exposure time - seconds
σ^2 = variance of detector granularity
n_s = number of spectrum diodes per resolution element
n_b = number of diodes smoothed over in background

The signal to noise ratio of the net spectrum is:

$$\left\{\frac{S}{N}\right\}^2 = \frac{S^2 t}{S\left\{\frac{1+b}{n_s f} + \frac{b}{n_b(1-f)} + \sigma^2(1+b)^2 St\right\} + d\left\{\frac{1}{n_s f} + \frac{1}{n_b(1-f)}\right\}} \qquad (1)$$

This model has been compared to experimental data obtained during the ground-based calibration, and all of its significant scaling relations have been confirmed. Rarely will all of these effects be important during a single observation. Each influence can be seen more clearly by considering the following limiting cases.

2. IF ONLY PHOTON NOISE IN THE SPECTRUM IS IMPORTANT

If the signal is much greater than the dark count, scattered light is not significant, and the granularity can be ignored, then $d=0$, $b=0$, $\sigma^2=0$, and $f=1$. Equation (1) reduces to the familiar result:

$$\left\{\frac{S}{N}\right\}^2 = n_s St \qquad (2) \qquad n_s St = \text{net counts per resolution element}$$

We have found that for observations made with any of the first order gratings, (G140M, G160M, G200M, G270M, G140L), equation (2) describes the observed S/N for up to 5000 or so counts per resolution element.

3. THE EFFECT OF DARK COUNTS

Retaining terms which include d, but ignoring scattered light and granularity we find:

$$\left\{\frac{S}{N}\right\}^2 = \left[\frac{S/d}{S/d + 1}\right] n_s St \qquad (3)$$

Both detectors have been extremely quiet during the ground-based development; $d < 3{*}10^{-4}$ cts/diode sec (<2 cts/orbit). Unless they deteriorate significantly, or prove to be unexpectedly sensitive to radiation, dark counts should rarely affect the data quality.

4. THE EFFECT OF INSTRUMENTAL SCATTERED LIGHT

In the Echelle modes scattering from both the Echelle and the cross-disperser causes an elevated background level which is counted by the diodes. The fraction b is calibrated as a function of order, and ranges from 0.02 to over 0.5 at the shortest wavelengths. This scattered light source is not significant in any of the first order grating modes, where $b < 0.01$. For a fixed observing time, t, the S/N of the net spectrum will be maximized if $f \simeq 0.90 \pm 0.05$. The "standard substep patterns" implemented at the STScI reflect this fact (ref 2).

$$\left\{\frac{S}{N}\right\}^2 \simeq \left(\frac{f}{1+b}\right) n_s St \qquad (4)$$

Typically, $f \simeq 0.9$ and $b \simeq 0.2$, (ref 2) and S/N is reduced by about 15% compared to the ideal case. The exposure time must be increased by about 33% to compensate for the noise in the background bins.

5. THE EFFECT OF DETECTOR RESPONSE GRANULARITY

$$\left\{\frac{S}{N}\right\}^2 = \frac{1}{\frac{1}{n_s St} + \sigma^2} \qquad (5) \qquad\qquad \text{as} \quad n_s St \rightarrow \infty, \quad \frac{S}{N} \rightarrow \frac{1}{\sigma} \qquad (6)$$

σ is typically 0.01 or so. At low count levels the noise in the signal dominates, and equation (5) gives the same result as (2). As the collected signal counts increase, the photon noise decreases, and eventually becomes negligible compared to the granularity. Equations (1) and (5) describe the statistical effect of granularity, averaged over a wide spectral interval. At high S/N levels it will be desireable to actually remove the detector irregularities using an as yet to be defined flat-fielding type of procedure.

6. REFERENCES

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4. Ebbets, D.C., "The Effects of Scattered Light and Detector Response Non-Uniformities on Signal to Noise Characteristics of HRS Data", Proceedings of the Eighth Workshop on the Vacuum Ultraviolet Radiometric Calibration of Space Experiments, Boulder, 1987.

DISCUSSION

BAADE The S/N at high spatial frequencies is one but not the only quality indicator. As the internal flat field lamp illuminates the detectors directly (the dispersive elements are by-passed), how do you correct for low spatial frequencies ? In view of the very limited length of single spectra and the continuum of grating angles this appears a very important point.

EBBETS The low frequency variations will be included in the absolute radiometric calibration. Standard stars will be observed at approximately 25Å intervals in the medium resolution modes, and 5Å intervals in the Echelles. Observers who require this kind of flat fielding will either have to use the calibrated wavelength settings, or arrange for new calibration observations to be made. It may be possible to interpolate between calibrated positions, but we have not yet developed such procedures.

SODERBLOM What is (are) the best achievable S/N with the HRS ? Your curve for the echelle mode suggest an asymptote value of around 150.

EBBETS With the medium resolution gratings (R=20000) S/N should be limited by Poisson statistics. It should be possible to achieve S/N > 100 without extraordinary effort, and perhaps 200 or more with careful observing and data reduction techniques. In the Echelle modes, S/N up to 50 or so will be determined by photon statistics. Observing techniques to remove the effects of scattered light and detector irregularities should allow S/N 700 to be achieved. We have plans to develop these techniques in the post-launch calibration program.

SNEDEN Have you had any problems with the lifetimes of Digicon detectors, and do you expect any additional problems after launch ?

EBBETS Both HRS detectors are now three years old, and continue to perform flawlessly. Tests are being run every few months while HST awaits launch. We measure dark count rates, resolution, geometrical stability, sensitivity, "dead-time" effects, and anomalous channels. A "pulse height analysis" sets the discriminator thresholds and searches for ion counts, which could be indicative of a leak in the vacuum seals. We expect the detectors to perform well for many years in orbit, after the 1 atmosphere pressure differential is removed.

FITZPATRICK What is the spatial scale of the photocathode granularity in the short wavelength detector ; and will the features be mapped ?

EBBETS The most troublesome structure has a spatial scale of 200 μm or so, which is comparable to the 50 μm resolution element. The irregularities will be mapped at a small number of wavelengths during the post launch "science verification" calibration program. These wavelengths have been selected to coincide with important interstellar lines. More comprehensive mapping may be undertaken as a long term calibration project by the Space Telescope Science Institute.