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TITLE: UV Grating Performance in the High Resolution Spectrograph

AUTHOR: Bottema, Cushman, Holmes, Ebbets

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ABSTRACT

This is a paper presented at the SPIE conference "Instrumentation in Astronomy V" in September 1983. It describes the results of laboratory testing and calibration of the dispersive modes of the HRS. Our current understanding of efficiency, resolving power, spurious images, scattered light, and the Echelle blaze function are discussed.
UV-grating performance in the High-Resolution Spectrograph

M. Bottema, G. W. Cushman, A. W. Holmes
Ball Aerospace Systems Division
Boulder, Colorado 80306

D. Ebbets
Space Telescope Science Institute
Baltimore, Maryland 21218

Abstract

The High-Resolution Spectrograph (HRS) covers the 105 nm to 320 nm wavelength range at nominal spectral resolutions 103, 104 and 105. It employs one ruled, plane, first-order grating (600 grooves/mm), four holographic, plane, first-order gratings (3600, 4320, 4960 and 6000 grooves/mm), one r/2 echelle (316 grooves/mm) and two ruled, multi-partite, concave cross dispersers (88 and 198 grooves/mm). These gratings are all replicas. The absolute efficiencies of the first-order gratings were measured by the Goddard Space Flight Center (GSFC) before integration into the HRS. The spectral resolution was derived from line-width measurements in the Pt spectrum during pre-flight calibration of the complete instrument at the Ball Aerospace Systems Division (BASD). Relative scattered-light levels were determined from gaseous absorption spectra. In some of the holographic gratings spurious images were observed parallel to the spectra. In the echelle the effective blaze angle in the UV was derived from relative-efficiency measurements and found to be about 62.8°. The spectral resolution and the scattered-light background were measured by the same techniques as above. Ghosts were detected at 0.45 interorder distances. Their relative intensities are less than 0.1% at 150 nm.

Introduction

The HRS offers the observer a choice of seven spectrographic modes of operation. The first one employs a first-order grating that covers the wavelength range from 105 nm to 170 nm with a spectral resolution $R = 1.8 \times 10^4$. The next three cover the wavelength range 115 nm to 320 nm in three overlapping sections with the same nominal resolution. The fifth mode duplicates mode 1 with a lower resolution but higher photometric sensitivity. Modes 6 and 7 offer a spectral resolution $R = 8 \times 10^4$ in the wavelength ranges 105 nm to 170 nm and 170 nm to 320 nm, respectively. These share a 316 groove/mm, r/2 echelle but use different cross dispersers. In addition, there are four camera modes, in which undispersed images of the spectrograph slits can be formed to assist in target acquisition. Modes 1, 5 and 6 share a 500-diode Digicon detector with a CsI photocathode and a LiF window. The remaining modes share a similar detector with CsTe photocathode and a MgF2 window. The diode width is 40 µm. The pixel width (diode center-to-center distance) is 50 µm. The width of a spectral resolution element, calculated from a convolution with the largest optical aberrations in the field and remaining irreducible focus and alignment errors, is estimated to be at most 65 µm. The spectral-resolution ranges in each mode, corresponding to the latter width, are listed in Table 1. The detector covers only small wavelength intervals at a time, as shown.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Wavelength range (nm)</th>
<th>Spectral order</th>
<th>Spectral resolution ($x 10^4$)</th>
<th>Detector</th>
<th>Wavelength interval (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105 - 170</td>
<td>1</td>
<td>1.4 - 2.5</td>
<td>CsI/LiF</td>
<td>2.9 - 2.7</td>
</tr>
<tr>
<td>2</td>
<td>115 - 210</td>
<td>1</td>
<td>1.2 - 2.5</td>
<td>CsTe/MgF2</td>
<td>3.6 - 3.3</td>
</tr>
<tr>
<td>3</td>
<td>160 - 230</td>
<td>1</td>
<td>1.5 - 2.3</td>
<td>CsTe/MgF2</td>
<td>4.1 - 3.8</td>
</tr>
<tr>
<td>4</td>
<td>220 - 320</td>
<td>2</td>
<td>1.7 - 2.8</td>
<td>CsTe/MgF2</td>
<td>4.9 - 4.5</td>
</tr>
<tr>
<td>5</td>
<td>105 - 170</td>
<td>1</td>
<td>0.14 - 0.22</td>
<td>CsI/LiF</td>
<td>29.0 - 29.1</td>
</tr>
<tr>
<td>6</td>
<td>105 - 170</td>
<td>53 - 33</td>
<td>6.8 - 7.6</td>
<td>CsI/LiF</td>
<td>0.55 - 0.95</td>
</tr>
<tr>
<td>7</td>
<td>170 - 320</td>
<td>33 - 18</td>
<td>6.5 - 8.4</td>
<td>CsTe/MgF2</td>
<td>0.85 - 1.79</td>
</tr>
</tbody>
</table>

The purpose of this paper is to review the performance characteristics of the gratings in each of the modes. An overview of their physical characteristics and their origin is given in Table 2. The gratings in modes 1 through 4 are replicas of holographic gratings, all specially generated by Instruments S.A. (ISA). The one in mode 5 is a replica of a mechanically ruled Hyperfine, Inc. (HYP) grating. The echelle is a standard Bausch and Lomb (B&L) replica. Originally, a newly ruled echelle was planned, specifically optimized for the HRS. However, one surpassing the existing echelles in quality could not be completed in time.
The cross dispersers are replicas of multi-partite, concave gratings, ruled specifically for the HRS by Hyperfine, Inc. All gratings are coated with Al and MgF₂. The thickness of the latter was chosen to maximize the reflectivity at either 122 nm or 160 nm, as indicated in Table 2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Manufacturer</th>
<th>Blank material</th>
<th>Blank size (mm²)</th>
<th>Ruling freq. (mm⁻¹)</th>
<th>Blaze angle (deg.)</th>
<th>Coating optimum (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>holographic</td>
<td>ISA</td>
<td>Optosil</td>
<td>88 x 153</td>
<td>-</td>
<td>-</td>
<td>122</td>
</tr>
<tr>
<td>2</td>
<td>holographic</td>
<td>ISA</td>
<td>Optosil</td>
<td>88 x 153</td>
<td>4960</td>
<td>-</td>
<td>122</td>
</tr>
<tr>
<td>3</td>
<td>holographic</td>
<td>ISA</td>
<td>Optosil</td>
<td>88 x 133</td>
<td>4320</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>4</td>
<td>holographic</td>
<td>ISA</td>
<td>Optosil</td>
<td>88 x 153</td>
<td>3600</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>ruled</td>
<td>HYP</td>
<td>Zerodur</td>
<td>88 x 93</td>
<td>600</td>
<td>2.23</td>
<td>122</td>
</tr>
<tr>
<td>6</td>
<td>echelle</td>
<td>B&amp;L</td>
<td>Cervit C-101</td>
<td>88 x 258</td>
<td>316</td>
<td>63.4</td>
<td>122</td>
</tr>
<tr>
<td>7</td>
<td>cross disperser</td>
<td>HYP</td>
<td>Cervit C-101</td>
<td>89 x 200*</td>
<td>194.6</td>
<td>0.7</td>
<td>122</td>
</tr>
</tbody>
</table>

* Off-axis paraboloid, focal length 1460 mm, decenter distance 170 mm, 6-partite
** Off-axis paraboloid, focal length 1340 mm, decenter distance 162 mm, 8-partite

In the following sections we discuss each of the gratings individually. We review the efficiency, the measured spectral resolution, as compared to the theoretical data in Table 1, and also some peculiarities that came to light during the calibration of the HRS. We precede this with a description of the experimental techniques employed.

Test facility

System-level testing of the complete instrument was carried out at BASO in a 3-m diameter vacuum chamber. The instrument was placed on a vibration-isolated table and its operating temperature could be adjusted isothermally between -10°C and 20°C.

The spectrograph slits were illuminated through an optical relay system that can accommodate an argon mini-arc, which is a calibrated U/V continuum source, traceable to the National Bureau of Standards, or a platinum/neon hollow-cathode lamp. The assembly is called the Space-Telescope Simulator (STS) and consists of two parts (Figure 1). One is a collimator, bolted to the outside of the door of the vacuum chamber, the other a refocussing off-axis paraboloid, mounted on the HRS fixture. Collimation makes the STS immune to lateral motions between its two parts. To also assure immunity against angular motions, the collimator field stop is set to overfill the small spectrograph slit and to underfill the large slit. The refocussing paraboloid can be remotely controlled to illuminate either one. The STS is made slightly slower than the Space Telescope (ST), i.e., f/26 instead of f/24, to allow for this motion and make alignment with the HRS less critical. The f number is defined by a stop in the refocussing section. It has a shutter to prevent accidental overexposure by closing automatically whenever the grating carousel is moved.

![Figure 1. Space-Telescope simulator](image)

The external part of the STS is kept under high vacuum and can be isolated from the chamber by means of a gate valve. This section is also fitted with a filter wheel and a removable 10-cm gas-absorption cell, used in scattered-light measurements (see below).

Communication with the HRS took place through a computer. Although software was available to conduct tests in near-real-time, most of the observations were performed with the
actual HRS flight software. Each test was coded in advance and executed as if the HRS were operating on orbit. Details are given in a companion paper.\(^\text{1}\)

Ground-based characterization of the HRS is still in progress. The instrument will be returned to BASO in 1984 for installation of a detector with improved high-voltage performance and for subsequent re-testing.

**First-order gratings**

**Efficiency**

All four holographic gratings were coated at GSFC under the direction of J. Osantowski. The spectral efficiency was subsequently measured at the Johns Hopkins University by J. Stolarik of GSFC. Use was made of the equipment, developed originally for the evaluation of gratings for the International Ultraviolet Explorer. The results of these measurements are summarized in Figure 2. Although a holographic grating can not be blazed in the conventional sense, the efficiency can rather well be optimized for a given wavelength range. In modes 1, 2 and 3 the efficiency peaks near 25% and exceeds 15% over most of the individual ranges. At any wavelength between 125 nm and 190 nm the efficiency exceeds 20% in at least one of the three modes. In mode 4 the efficiency at short wavelengths is 20%. Above 260 nm it increases to 45% or more. The ruled grating in mode 5 is blazed at 130 nm. It has more than twice the efficiency of the grating in mode 1, with a peak value of 53%. It was coated by Acton Research Corp., Acton, Massachusetts.

![Figure 2. Absolute efficiency of first-order gratings](image)

![Figure 3. System photometric sensitivity in counts diode-1 s-1 for an irradiance at the telescope aperture of 1 photon cm-2 s-1 nm-1](image)

For comparison we show in Figure 3 the combined sensitivity of the ST and HRS in terms of photon counts per diode per unit spectral irradiance at the ST aperture stop, on the basis of system-level calibrations. The system sensitivity is mainly determined by the product of grating efficiency, dispersion and detector response. The latter is discussed in detail elsewhere. The difference in dispersion leads to a sensitivity ratio of more than an order of magnitude between modes 5 and 1. The combination of grating efficiency and detector response has the effect of flattening the system response in modes 2 and 3, and causing a roll off at long wavelengths in mode 4.

**Resolving power**

The theoretical resolving power is defined by

\[ R = 2(f/s)\sin\gamma\cos\delta/\cos(\gamma-\delta), \tag{1} \]

where \( f \) is the camera focal length, \( s \) the width of the spectral resolution element, \( \gamma \) the grating scan angle and \( \delta \) half the deviation angle between the incident and diffracted beams. These parameters are related to the wavelength \( \lambda \) by

\[ 2\sin\gamma\cos\delta = m\lambda/(d\cos\gamma) \tag{2} \]

where \( m \) is the grating constant, \( \gamma \) half the off-plane angle and \( m \) the spectral order. In modes 1 and 5 \( f = 1425 \text{ mm} \) and \( 2\gamma = 14.29^\circ \). In modes 2, 3 and 4 \( f = 1350 \text{ mm} \) and \( 2\gamma = 6.75^\circ \). In all of these modes \( 2\gamma = 4^\circ \) and \( m = 1 \).
The prediction of the theoretically achievable resolving power depends entirely on the value of \( s \). An absolute lower limit is the center-to-center distance of the diodes \((s = 50 \, \mu m)\). A realistic upper limit can be calculated by convoluting this distance with the geometrical aberrations in the field, the chromatic aberrations in the detector window, irreducible residual focus and alignment errors and diffraction. This leads to \( s = 55 \, \mu m \) at the center of the photocathode and to \( s = 65 \, \mu m \) in the corners. The theoretical resolution in modes 1, 2, 3 and 4, thus calculated, is plotted in Figure 4 as a function of wavelength. The performance goal, set for these modes, was a resolution of \( 1.85 \times 10^4 \). As the diagram shows, this should be achievable at any wavelength above 125 \( \mu m \) in at least one of the modes, even with \( s = 65 \, \mu m \).

![Figure 4. Theoretical spectral resolution in modes 1, 2, 3 and 4 for resolution-element widths \( s = 55 \, \mu m \) and \( s = 65 \, \mu m \).](image)

The resolution was determined experimentally by scanning isolated Pt lines across a single diode in steps of 25 \( \mu m \). The full width at half maximum (FWHM) of the profile, thus obtained, is considered to be the equivalent of \( s \) in Eq. (1). In each mode, about 20 measurements were made, distributed over various wavelengths and diode locations. The Pt lines used are isotopic triplets, but cannot be resolved in the first-order modes. The separation between the outer components is less than 0.006 nm.

In mode 1 an average width of 75 \( \mu m \) was found for diodes numbered 200-500. However, for lower-numbered diodes, the width increases rapidly to near 100 \( \mu m \) at the end of the array. The same trend, but much less pronounced, was found in mode 5. Here the width decreases from 76 \( \mu m \) (diodes 1-100) to 70 \( \mu m \) (diodes 400-500). At the present time we are inclined to attribute the low resolution in mode 1 mainly to optical imperfections in the grating, which undoubtedly is used in a configuration quite different from that in which it was holographically generated. The data for mode 5 would indicate that possibly there is still either a residual alignment error and/or a focus error, combined with a difference in tilt between the spectrum and the detector. When the HRS was aligned, the detector was intentionally adjusted to match the echelle spectrum, rather than the first-order spectra. On the basis of the HRS design the tilt difference should be acceptably small.

In modes 2 and 3 the measured widths ranged from 55 \( \mu m \) to 70 \( \mu m \). This shows that the theoretical resolution can indeed be reached. In mode 4 the width was again larger, with an average of 87 \( \mu m \). This mode shares the optical train with modes 2 and 3, except that an order sorter is present. Separate interferometric tests showed that its contribution to image blur should be small. This still leaves the grating as a possible additional source.

Spurious images

In mode 1 spurious images were observed at equal distances above and below the main spectrum. Each of the images is double, but otherwise sharply defined. The distances were found to be proportional to wavelength. At 140 nm the value is about 3 mm. These characteristics identify the origin as a periodic structure with about 14 waves/mm, orthogonal to the main grating and extending over its entire area. The images are innocuous with regard to background measurements. The relative intensity lies between 0.5% and 1%. Spurious reflections in the generating optics of the grating might be a possible cause.

In mode 4 the spectrum is accompanied on one side by a series of regularly spaced images of declining intensity. These are tentatively attributed to multiple reflections between
the grating and the order sorter, although their relative intensities (5%, 0.6% and 0.1%, in descending order) seem somewhat too high to be compatible with this explanation. We do not exclude the possibility of a phenomenon, similar to that in mode 1. Here again, there is no impact on background measurements.

No spurious images of any kind were detected in modes 2 and 3. However, there is an artifact, common to all modes, that is caused by specular reflections from a high-voltage ring in the detector. Its source lies about 0.5° outside the field. The relative intensity is about 0.1%. Allowance for this background must be made in instrument planning and data analysis. There is no way to eliminate it altogether but a less reflective material will be used in the replacement detector, to be installed in 1984.

Scattered light
Scattered light may originate from residual random errors in groove positions and groove profiles in ruled gratings, and from surface roughness in both ruled and holographic gratings. In addition, there may be small contributions from baffle edges and other structural elements. In general, the distribution in the spectrum will be different from that perpendicular to the spectrum.

Two methods of evaluation were used: a) measurement of the distribution near strong emission lines and b) measurement of the background level in saturated gaseous absorption bands. The latter is not as simple but more relevant to the interpretation of astronomical absorption spectra.

Examples of scattering in the vicinity of the 254-nm Hg line in modes 3 and 4 are shown in Figure 5. The distance from the line is expressed as an equivalent wavelength difference $\Delta \lambda$. The curves represent the so-called "grating scatter function"$^6$, i.e., the number of counts per unit wavelength $1(\Delta \lambda)$, divided by the number of counts in the line $I_{\lambda}$, as a function of $\Delta \lambda$. This form of presentation permits direct comparisons of different gratings. Several grating scan-angle settings were required to cover the $\Delta \lambda$ range shown. The features near the ends of the curves are the detector reflections at 0.5°, mentioned above.

![Figure 5](image1)
Figure 5. Grating scatter functions on either side of the 254 nm Hg line in modes 3 and 4

![Figure 6](image2)
Figure 6. CO (3-0) absorption band in mode 1

The gaseous absorption technique is illustrated by Figure 6. It shows the (3-0) band of CO at a pressure of 5 torr in a 10-cm path at room temperature in mode 1. The band-head wavelength is 144.7 nm. The continuum spectrum was generated by the Ar mini-arc. The count rate in the absorption core is only about 0.1% of that in the continuum. The scattered-light background outside the spectrum was measured concurrently, either by electronic deflection of the spectrum or by a direct reading on one of four special background diodes above and below the main diode array. If we assume this background to be uniform, the contribution from grating imperfections can be found by subtraction. In modes 1, 3 and 4 this leads to very small residuals (Table 3). In modes 3 and 4 the (13-0), (12-0) and (11-0) Schumann-Runge bands of O$_2$ between 178 and 181 nm were observed, the gas flowing through the 10-cm cell at one atmosphere and room temperature. No conclusive data are as yet available for modes 2 and 5. In the latter the O$_2$ bands are not saturated. Only an upper limit of 8% can be inferred.
Table 3. Scattered light in first-order modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption band</td>
<td>(3-0)C0</td>
<td>(11-0)O2</td>
<td>(11-0)O2</td>
<td>(11-0)O2</td>
</tr>
<tr>
<td>Background</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>&lt;0%</td>
</tr>
<tr>
<td>Grating contribution</td>
<td>nil</td>
<td>0.5%</td>
<td>nil</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Echelle

Effective blaze angle

The blaze angle of the echelle is listed in the B&L catalog as $\arctan 2 = 63.4^\circ$. Measurements at B&L indicated, however, an actual effective blaze angle in the UV closer to $62.8^\circ$. As will be shown presently, this number is consistent with independent measurements at BASD. By effective blaze angle we mean here the blaze-angle value that gives the best match to experimental data if the theoretical relative efficiency is represented by

$$E = (\cos(\gamma + \delta)/\cos(\gamma - \delta))\text{sinc}^2(m\pi\cos(\gamma + \delta)\sin(\gamma - \delta)/\sin\gamma).$$

(3)

This equation applies to an in-plane configuration in which the angle of incidence $\alpha = \gamma + \delta$ is larger than the angle of diffraction $\beta = \gamma - \delta$.

Examples of $E$ as a function of $\gamma$ are given in Figure 7 for $m = 36$, $26 = 12.75^\circ$ (mode 6) and two values of $\delta$, i.e., $\delta = 68.2^\circ$ and $\delta = 63.4^\circ$. These show that the ratio of the efficiencies in two consecutive orders of the same wavelength is a strong function of $\delta$. Hence, measurements of this ratio permit an accurate determination of this angle.

Figure 7. Theoretical echelle efficiencies in mode 6 for echelle blaze angles $\theta = 62.8^\circ$ and $\theta = 63.4^\circ$. In the first case the ratio between orders 37 and 36 is 1.0, in the second case 2.6.

Figure 8. Spectral reflectivity of echelle witness mirrors.

During calibration of the HRS in mode 6, efficiency ratios were obtained for the Pt line at 140.4 nm and the Cl line at 156.1 nm. In both cases three consecutive orders could be observed. The blaze angles, derived from the efficiency ratios, are shown in Table 4. The central orders are very strong, but the outer orders are weak and, therefore, subject to large photometric errors. Also, there is some doubt whether Eq. (3) remains applicable at these orders in view of the highly simplified model assumed for diffraction by the groove. Much greater accuracy in the determination of $\theta$ can be achieved with wavelengths near the ends of the free spectral range, such as shown in Figure 7. Such measurements are planned as the calibration of the HRS continues.

Table 4. Effective echelle blaze angles

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Orders compared</th>
<th>Blaze angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140.4</td>
<td>39 to 40</td>
<td>62.8 ± 0.06</td>
</tr>
<tr>
<td>140.4</td>
<td>41 to 40</td>
<td>62.5 ± 0.1</td>
</tr>
<tr>
<td>156.1</td>
<td>35 to 36</td>
<td>62.8 ± 0.05</td>
</tr>
<tr>
<td>156.1</td>
<td>37 to 36</td>
<td>62.6 ± 0.1</td>
</tr>
</tbody>
</table>
Absolute efficiency  
The absolute efficiency is the product of the relative efficiency in Eq. (3) and the effective reflectivity of the groove facets. In theory, R_g should be close to the reflectivity of mirrors, coated simultaneously with the echelle. Measurements in visible and the near UV on various echelles at B&L indicate that R_g can indeed, be as high as 0.8 R_m or more. The HRS echelle was coated at the GSCF. The measured values of R_m are shown in Figure 8. No direct measurements of the absolute efficiency of the echelle were possible for lack of space in the available equipment. However, throughput measurements of the HRS suggests that here, too, fairly high values of R_g were realized.

Spectral resolution  
The theoretical resolution is given by Eq. (1). The fixed constants are f = 1460 mm, δ = 6.375° in mode 6 and f = 1340 mm, δ = 2.875° in mode 7. Within each spectral order the efficiency peaks near γ = 0. The corresponding wavelength is $\lambda_\gamma = 2d\sin\theta\cos\delta$. The free spectral range is centered on this wavelength and covers an interval $\Delta\lambda = \lambda_\gamma / n$. The corresponding theoretical resolution ranges are listed in Table 5 for the lowest and highest orders in each mode. These are calculated for resolution-element widths s = 55 μm and s = 65 μm. The latter are the basis for the summary data in Table 1. We note that for an actual blaze angle $\theta = 62.8°$ the overall resolution will be 2% less than for the nominal blaze angle $\theta = 63.4°$ and 25% less than for the r/2.5 echelle with $\theta = 68.2°$, originally planned. However, in some cases it should be possible to observe at scan angles beyond the upper limit of the free spectral range and thus regain some of the intended resolution potential, be it at the expense of lower efficiency.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Order</th>
<th>Width resolution element (μm)</th>
<th>Lower wavelength limit (nm)</th>
<th>Spectral resolution (x10^5)</th>
<th>Upper wavelength limit (nm)</th>
<th>Spectral resolution (x10^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>33</td>
<td>55</td>
<td>166.9</td>
<td>8.08</td>
<td>172.1</td>
<td>9.03</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>65</td>
<td>104.5</td>
<td>8.18</td>
<td>106.5</td>
<td>8.82</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>55</td>
<td>303.6</td>
<td>7.72</td>
<td>312.0</td>
<td>9.87</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>65</td>
<td>167.8</td>
<td>8.11</td>
<td>172.9</td>
<td>9.26</td>
</tr>
</tbody>
</table>

The actual resolution in mode 6 was derived from scans of several Pt lines at various locations in the diode array. At 170 nm an average width of 60 μm was found, in excellent agreement with the theoretical prediction. However, at smaller wavelengths the width becomes systematically larger, with an average near 80 μm at 125 nm (Table 6). This effect is tentatively attributed to broadening of the electron images at the diodes, caused by the higher energy, imparted on the photoelectrons at the photocathode. This may also be a contributing factor in the resolution losses, observed in modes 1 and 5. In addition, the isotopic separation in some of the Pt lines may approach the resolution limit in mode 6. No correlation was found between width and diode location. This, together with the high resolution at 170 nm, indicates that focus and alignment in mode 6 are within achievable limits.

<table>
<thead>
<tr>
<th>Wavelength range (nm)</th>
<th>FWHM range (μm)</th>
<th>Mean Value (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1240 - 1250</td>
<td>72 - 90</td>
<td>79</td>
<td>7</td>
</tr>
<tr>
<td>1400 - 1405</td>
<td>59 - 78</td>
<td>69</td>
<td>7</td>
</tr>
<tr>
<td>1505 - 1510</td>
<td>64 - 74</td>
<td>67</td>
<td>4</td>
</tr>
<tr>
<td>1705 - 1710</td>
<td>54 - 70</td>
<td>59</td>
<td>8</td>
</tr>
</tbody>
</table>

The above measurements were preceded by a screening test, in which special 25-μm wide calibration diodes were scanned. Three of these are located at each end of the main array. In mode 6 the width, thus measured, was 50 μm at 151 nm. However, in mode 7, it was as large as 75 μm at 270 nm. The excess width is attributed to optical imperfections in the fused-silica order sorter, which must be present to suppress second-order cross-disperser spectra. The order sorter has subsequently been finished and new measurements have been planned.

Ghosts  
The 316 groove/mm echelle is known to exhibit pairs of faint ghosts about midway between the orders. B&L attribute these to serve integration in the interferometric control system of the ruling engine and quote the distance from the parent lines to be $d_m = 0.412$. In the HRS echellegram these ghosts are readily recognized as faint spectral images in the inter-order spacings. Quantitative measurements were made at 254 nm in mode 7 and at 149 nm.
in mode 6. The distances from the parent lines were found to fit $\Delta m = 0.455$, rather than the B&L value, which was probably determined in visible light. The relative intensities were found to be $(2.1 \pm 0.1) \times 10^{-4}$ at 254 nm and $(5.1 \pm 0.6) \times 10^{-4}$ at 149 nm. If the ghosts are interpreted as Lyman ghosts, these data are compatible with a periodic groove-position error of 114 cycles/mm and an amplitude of 0.6 nm. The relative intensities should then be proportional to $x^{-2}$, which fits the data rather well. By extrapolation, the corresponding relative intensity in the visible would be $3 \times 10^{-5}$. B&L do not give quantitative data but describe the ghosts as just perceptible at 633 nm.

Scattered light

Scattered light in the echellogram arises mainly from echelle ruling imperfections. It appears between the spectral orders in the form of numerous ghost images, often referred to as "grass". The average light level is proportional to $m^2$.

The gaseous absorption technique was used to analyze the scattered-light distribution. In mode 6 the CO (3-0) band near 144 nm was observed. In the spectrum the area of saturation was found to be filled in to 20% of the continuum level (Figure 9). Also measured were the backgrounds in the adjacent inter-order spacings above and below the spectrum. At 144 nm the orders are sufficiently separated to do this by displacing the spectrum in the cross-dispersion direction. The two backgrounds show some structure and are not quite identical. However, when a smoothed average was taken and subtracted from the spectrum, the level left in the absorption core was only 1% of the continuum. In mode 7 the (11-0) band of $O_2$ was observed. The absorption cores were filled in to about 23% of the continuum, but may not have been completely saturated (Figure 10). Here also the orders are sufficiently separated to allow inter-order background measurements by displacement of the spectrum. Subtraction after smoothing and averaging left a residue of about 2.5% of the continuum level in the absorption cores. It thus appears that most of the echelle scattering can be removed from the spectral data but the uncertainty in the residue is still far greater than in the holographic-grating modes.

![Figure 9. CO (3-0) absorption band in mode 6. The upper curve represents the raw photon count per diode. The lower curve is the smoothed average of the inter-order backgrounds on either side of the spectrum](image1)

![Figure 10. O$_2$ (11-0) absorption band in mode 7. The upper curve represents the raw photon count per diode. The lower curve is the smoothed average of the inter-order backgrounds on either side of the spectrum](image2)

Cross dispersers

The cross dispersers were coated by Acton Research Corp. The absolute efficiencies were subsequently measured by the GSFC. In mode 6 each partition is about 15 mm wide. A scan with a 10-mm beam revealed the associated fluctuation in efficiency but also showed that the mean value varied little from one partition to the next. The average values across the grating are:

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>128.9</th>
<th>150.9</th>
<th>177.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute efficiency</td>
<td>44.5</td>
<td>38.0</td>
<td>34.7</td>
</tr>
</tbody>
</table>

In isolated, bright spectral images scattered light from residual grating imperfections appears as a line in the cross-dispersion direction. This forms part of the general background in the echellogram. No quantitative assessment of this contribution was made.
Conclusions

In the middle-resolution modes completely satisfactory grating performance is achieved in modes 2 and 3. In modes 1 and 4 the images are about a factor 1.5 wider than was expected.
In mode 1 this is most likely caused by wavefront errors in the difficult to generate high-frequency grating. In mode 4 wavefront errors in the order sorter may be one of the causes, possibly combined with grating imperfections. In modes 1 and 4 spurious images are present, which may be related to grating imperfections but are not detrimental to performance. In all four modes scattered-light levels are very low.

In mode 5 the resolution is also somewhat lower than expected. Possible causes are a small mismatch in tilt of the spectrum and the detector, residual alignment errors and broadening of the electron image at short wavelengths. We note, however, that in this mode spectral resolution is less important than high efficiency.

In the high-resolution modes good image quality is achieved in mode 6 but not in mode 7. This is probably due to optical imperfections in the order sorter. In both modes scattered light levels are high (20% or more) but adequate correction by inter-order background measurements seems feasible.

All of the above reflects the status of May, 1983. Some improvements may be possible when the HRS is returned to BASD for further calibration in 1984.

Acknowledgements

The material presented here was derived from the calibration of the HRS at BASD. A paper on the calibration results in general precedes this one in the same volume.8 The HRS is developed by the Investigation Definition and Experiment Development Teams under the direction of J. C. Brandt, Principal Investigator.9,10 The present paper represents but one facet of the total team effort.

References

8. Brandt, J. C., SPIE Proc., this volume