Comparison of low-cost hyperspectral sensors

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Recent advances in large format detector arrays and holographic diffraction gratings have made possible the development of imaging spectrographs with high sensitivity and resolution, at relatively low component cost (<$100K.). Several airborne instruments have been built for the visible and near infrared spectral band with 10-nm resolution, and SNR of 200:1. Three instruments are compared, an all-reflective spectrograph using a convex grating in an Offner configuration, and two off-the-shelf transmission grating spectrographs using volume holograms. The camera is a 1024 x 1024 frame transfer, back-thinned CCD, with four taps for obtaining high frame rates. Performance and scan data is presented and compared to the design for image quality, distortion, and throughput.

Keywords: imaging spectrograph, hyperspectral, convex holographic gratings, holographic transmission gratings

1. INTRODUCTION

The utility of hyperspectral imaging in classification and discrimination of various terrestrial backgrounds has been demonstrated with imagery from the AVIRIS and HYDICE airborne sensors. In an imaging spectrograph, a narrow swath is imaged by a fore-optics lens onto a narrow slit, which is then relayed and spectrally dispersed across each detector row, while retaining the spatial information along each detector column. The scene is pushbroom scanned using motion of the platform to obtain a three-dimensional “image cube”, with two spatial dimensions and one spectral dimension. The spectra of each field location are then processed to yield data products on bathymetry, bottom type, surface reflectance, or a host of other water and land classification maps. Grating spectrographs are becoming available at lower cost and high performance, making them a suitable solution to many science and military applications. An assessment of the performance of three particular grating spectrographs is presented, with a discussion of spectral imagery from one of these sensors.

2. BACKGROUND

Larger format detector arrays have extended the flexibility of designing high resolution, high signal-to-noise imaging spectrographs, allowing for wider swaths and higher spectral resolution, even for low albedo scenes such as the coastal environment. Format sizes of 1024x1024 in frame transfer CCDs are becoming established above video rates with <50 electrons read noise and >60000 electrons well depths, well suited for spectrograph fluxes. Grating imaging spectrographs have been shown to have certain advantages over other hyperspectral technologies such as those incorporating prism, wedge filter, and interferometric techniques. The primary advantage is the simultaneity in acquisition of linearly dispersed spectrum without the need of post-processing, other than non-uniformity correction of the detector. The main limitations that traditional grating based systems have typically encountered are correcting for apertures faster than f/4, multiple diffraction orders, and polarization effects. Other problems associated with imaging spectrographs are the change of dispersion angle with field position (smile), and change of magnification with spectral channel (spectral keystone). These distortions (Figure 1) limit the robustness of subpixel discrimination and detection algorithms.

The two main approaches in grating spectrographs are reflective surface relief gratings and volume transmission holograms. Traditional reflective mountings, such as Čzerny-Turner and Ebert types, have a limited flat field and large spot sizes. By varying the groove density across the grating aperture, some degree of aberration correction can be obtained with these mounts, but would still be insufficient for the current application. An aberration-corrected concave grating in a Rowland mount, is a second improvement, but also falls short of the 8 to 25 micron pixel pitch of large format science grade CCDs. The Offner spectrograph offers a significant improvement in both distortion and image quality, and will be explored further in this paper.

Volume holographic grating are manufactured by recording the interference pattern of two wavefronts in a photosensitive material such as dichromated gelatin or DuPont photopolymer. The refractive index modulation and Bragg tilt of the film is controlled to yield the peak efficiency and desired dispersion in the diffraction order of interest. The prime limitations are obtaining high efficiency and transmission over the full spectral range of 0.4 to 1.0 micron. A prism or fold mirror can be used to align the diffracted beam to the optical axis of the imaging optics.
3. TRANSMISSION GRATING SPECTROGRAPH

Through combining commercial photographic lenses with a transmission holographic grating, the Holospec™, built by Kaiser Optical Systems Inc., is able to obtain a simple design while retaining high performance imaging. The spectrograph, shown in Figure 2., contains 75-mm focal length Nikon lenses, a fold mirror, and the transmission grating. For size comparison, the ImSpector™ spectrograph discussed next is shown in Figure 3. The field is defined by a 12-micron wide air slit, and the aperture stop determined by the grating aperture. The performance metrics of the spectrograph were evaluated by imaging onto a 1024 x 1024 CCD array with 12-micron pixels. A Schneider 25-mm, f/1.4 C-mount lens was used as the fore-optic for the image quality and throughput measurements. This lens was selected for its low distortion and correction for the broad spectral range of 0.4 – 1.0 microns, and to match the operational parameters for most of our airborne field deployments (1.5-m footprint, 80-knots ground speed, 3300-m altitude.) Variations in results are possible depending upon the selected fore-optic lens, and the accuracy of aligning and focusing the camera. Therefore, these results should provide a methodology for system integration, and not as a spectrograph selection guide.

![Fig. 1 Definition of Smile and Keystone Distortion](image1)

**Figure 2.** Holospec™ Spectrograph

**Figure 3.** ImSpector™
For characterization, three measurements taken were of a spectral line source, a bar target with a line source, and of a uniform field from an integrating sphere. From the sample spectrum of a Mercury lamp shown in Figure 4, the 577/579-nm doublet line could be discriminated over the full spatial range. The smile of the 405-nm line shown in Figure 5 was two pixels after rotation correction. The linearity of dispersion was calculated from the spectral lines to be +/- 0.5%. Ideally, the magnification should be constant with wavelength, however, from the image of a bar target in Figure 6, the system was observed to have 0.6% spectral keystone distortion (3 pixels), and a spatial blur size of approximately 2 pixels. With this particular lens/spectrograph system, some field curvature across the spectra was observed. The blur will be a convolution of the fore-optics lens point spread function, the slit, the spectrograph, and the detector sampling, and not just of the spectrograph alone.

The primary difficulties in all three spectrograph sensors are camera alignment, 0th-order diffraction suppression, and pupil matching. Low-noise cameras are often cooled to between –20 and 0 C, and thus require a dewar with a window to contain the detector and prevent condensation. This adds complexity in mounting an order-sorting filter near the detector, as well as trapping the 0th order diffraction prior to the window where it can introduce scattered light. The method for mitigating these issues is placing the order-sorting filter either directly on the detector or on the back surface of the window, and minimizing the distance from the detector to the window. The window tilt and wedge tolerances are very important to avoid introducing coma and keystone. Camera manufacturers typically include a window with a single layer MgF anti-reflection coating; this however may be insufficient in reducing scattered light for large spectral ranges here. In order to meet the mechanical constraints of their prospective applications, C-mount and photographic lenses have their exit pupils located from 10 to 50-mm in front of the image plane. However, being low-distortion 1-X relays, spectrographs are designed to be telecentric (entrance pupil at infinity), and thus do not match most available lenses. The result is significant vignetting in the spectrograph, especially for wide field-of-view lenses (< 25-mm focal length). The two easy solutions to the problem are operating the fore-optics at a faster f-stop, and accepting the higher scatter and lower image quality due to the stop shift, or the addition of a field lens at the entrance slit to match pupils. A better approach is to design and build a telecentric, low-distortion lens from the beginning and use the full capability of the selected spectrograph. These modifications will be taken in the next generation systems.

4. PRISM-GRAting-PRISM GRATING SPECTROGRAPH

The second spectrograph evaluated was the ImSpector™ built by Spectral Imaging Ltd. of Finland. The unique characteristics of this spectrograph are the small size, mounting ease, and common optical axis. Between sets of relay lenses is a cemented prism-grating-prism assembly to provide the necessary dispersion. The dispersion is primarily performed by the dichromated gelatin holographic grating, with the prisms compensating for the first order diffraction angle and providing a grating mounting surface. The degree of correction of smile, keystone, and image quality is determined by the complexity of the relay lens combination.

Similar to the previous measurements, spectra of Mercury lamps and a bar target were imaged, and are shown in Figures 7. The keystone was measured to be 0.8% with a four pixel (48 micron) spot size. The slit on this particular spectrograph was 27-micron, thus contributing to the large spot size. Evaluating a custom design based on a 1-X relay lens and optimizing, 12-micron rms blur sizes were obtained by the ray trace model, however the number and size of the required elements would negate the advantage of its small size.
Figure 6. HoloSpec™ Spectrograph Keystone Measurement

Figure 7. ImSpector™ Spectrograph Keystone Measurement

Figure 8. VS-15 Spectrograph Keystone Measurement
Since reflective surface gratings are in open literature, a more analytical approach was taken, as opposed to relying on generic system specifications given by transmission grating spectrographs for their proprietary designs. For the reflective design an Offner relay (Figure 9) was chosen due to its low distortion, high image quality, and the simplicity of an all-spherical design. Starting with a 2:1 curvature ratio and a common center point, the surface contributions to 3rd and 5th-order spherical, and 3rd and 5th-order coma are zero. The contributions between the primary and the tertiary are balanced to zero for 3rd order astigmatism, field curvature, tangential oblique spherical, and elliptical coma, with only 5th-order astigmatism remaining. With the addition of a convex grating on the secondary to provide the necessary dispersion, the axial ray strikes the primary and tertiary at different angles resulting in a degradation of the balancing of the off-axis aberrations. To compensate, the construction parameters of the grating and mirror tilts are added to the optimization variables. The slit and spatial direction is shown coming out of the paper.

For holographic gratings, the first construction point was initially chosen to be near the center of curvatures of the mirrors, with the second point displaced in the y-axis to provide the required groove density of the grating. The construction point positions, radii, tilt angles, and air space thicknesses are allowed to vary during optimization, with constraints being the linear dispersion determined by the detector area, and mirror separations sufficient to prevent obscuration. Centroid-based rms spot size was used for default merit function, with additional weights given to dispersion, spectral keystone and smile. During optimization, the construction sources moved to a longer distance from the substrate, and the tertiary incurred an additional tilt to balance of 3rd and 5th-order astigmatism. A fold mirror is required on the input due to mechanical constraints caused by the camera body size. The resultant spectrograph without folds, shown in Figure 10, is telecentric with the full 0.4 to 1.0 micron spectral range dispersed over 12 mm.

When tilt in the focal plane is used to compensate for longitudinal color in a spectral imaging system, keystone distortion is often an undesired consequence as well. From a ray trace, the maximum keystone distortion of the chief ray was 20 microns at the edge field and wavelength position. The disagreement from the measured value of 4 pixels (48-microns) shown if Figure 8, is most likely due to alignment error in the mirrors or in the grating recording process. Being greater than one pixel, further tightening during optimization and alignment is required. From the centroid locations, smile was calculated to be <1 micron over the full field and spectrum. This measured value of <1 pixel agrees with the ray trace to the extent of the resolution of the camera. At f/2, the design exhibited a spot size of 10-microns rms at the edge of the field, allowing margin for fabrication tolerances.
In a three-mirror spectrograph, the linear dispersion equals the tertiary mirror focal length multiplied by the angular dispersion of the grating. By changing the tertiary focal length, however, some accommodation can be given to the groove density of the grating. From the grating equation, \( n_1 \sin(\theta_1) - n_2 \sin(\theta_2) = m\lambda \), dispersion is also determined by the incident angle, which directly impact the astigmatism introduced by the secondary. The groove density is important from both an analytical and manufacturing viewpoint. The efficiency in diffracting incident light into the different orders can be predicted by scalar diffraction theory or electromagnetic theory. Scalar theory is sufficient for wavelength-to-groove pitch ratios of \( \lambda/d <<1 \), in which case the grating is approximated by a series of plane mirrors with a constant angle with respect to the surface normal. For low groove densities, the efficiency profile can also be approximated as the Fourier transform of the blaze profile. Groove densities lower than 40 grooves/mm are more difficult to manufacture and have less ability for aberration correction. The spectral resolving power can be approximated by the total number of grooves on the 25-mm substrate, corresponding to 1550 lines, much greater than the system requirement of 120 bands.

Convex gratings can be made either holographically or through direct e-beam writing of the grooves, with each technique exhibiting its own advantages and disadvantages. E-beam gratings can be made of an arbitrary groove density and blaze profile in one process step. The limitations are substrate size, scattered light, polarization, and cost. For holographic gratings, the only degrees of freedom are the position of the two spherical construction wavefronts. Aspheric construction wavefronts and/or grating substrates have not been shown to add significant advantage, although are a topic for further research. Once a master holographic grating has been constructed, precise duplicate gratings can be fabricated by examining the moiré fringe pattern between the master grating and the interference fringes of construction wavefronts. For aberration-corrected gratings created by convergent wavefronts, care must be taken to avoid aberrations and scattered light induced by the imaging optics of the sources. The blazing of the groove profile can be created in a separate process step of ion-etching the sinusoidal groove shape into a triangular groove shape.

The VS-15 groove frequencies were guided to 150 grooves/mm within scalar theory and manufacturability constraints. By changing the pitch to depth ratio, the peak of the efficiency curve can be shifted to a different wavelength. Ion-etching the blaze profile from a sinusoidal profile to a triangular profile can shift the diffraction efficiency from the \(-1\) into the \(+1\)-order, improving the average efficiency greater than 50%. However, since the spectral bands of interest are greater than one octave, the absolute efficiency cannot be over 50% at both ends of the spectral bands simultaneously. An important issue in the blazing process is maintaining a constant blaze angle with respect to the surface normal, which is not a concern with planar substrates.

Figure 11. Ocean Color Sensor with VS-15 Spectrograph
6. SCANNED SPECTRAL IMAGERY

The VS-15 Offner spectrograph system was mounted on a scanner, and imaged an outdoor scene. The goal of the experiment was to evaluate the operational image quality and constituent demixing computer models, as well as debug sensor problems. The sensor hardware included the spectrograph, PC-based data acquisition, RAID disk, tape backup, GPS, power converter, and power regulator, all within a 19-inch rack. Scans were recorded at 28 frames/second at f/2, with 128 spectral bands, sufficient for spectral discrimination algorithms. The Optical Realtime Adaptive Spectral Indentification System (ORASIS) algorithm was applied to the scanned data yielding multiple constituent spectral planes (shown in Figure 12.) The raw spectra, prior to gain and offset correction, exhibited the spectral signatures which one would expect, Raleigh scattering peak in the blue, a well defined red-edge in the vegetation, and easily defined atmospheric absorption lines (Figure 13).

![Building Endmember](image1)
![Grass Endmember](image2)
![Shadow Endmember](image3)

**Figure 12.** ORASIS Endmembers for Scanned Scene with VS-15 Spectrograph

![Spectral Profile](image4)

**Figure 13.** Scene Spectra
7. SUMMARY

Although transmission grating and reflective grating approaches have different advantages, the Offner reflective mounting is the most likely choice for most hyperspectral remote sensing systems. Both techniques provide image quality comparable to 1-X relays, however the Offner spectrograph has the advantages of lower smile, larger aperture, fewer components, larger field, and broader spectral range (Figure 14). Disadvantages are the immaturity of blazing on convex substrates, while retaining low polarization and scatter. Using a C-mount or an F-mount lenses for the fore-optics lens, although an easy and inexpensive solution, is inappropriate since the exit pupil does not match the entrance pupil of the spectrograph. As further development of commercial imaging spectrograph systems progresses, the performance of both transmission and reflective grating spectrographs will grow closer to the theoretical ray tracing results.

<table>
<thead>
<tr>
<th>Description</th>
<th>VS-15</th>
<th>Inspector</th>
<th>Holospec</th>
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<tbody>
<tr>
<td>Size (L x W x H)</td>
<td>100 x 100 mm</td>
<td>135 x 70 x 60 mm</td>
<td>180 x 240 mm</td>
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<tr>
<td>Spectral Range</td>
<td>400 – 1000 nm</td>
<td>430 – 900 nm</td>
<td>400 – 800 nm</td>
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<tr>
<td>f-number</td>
<td>f/2</td>
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<td>8.8-mm by 27-um</td>
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<tr>
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<td>Spectral Keystone</td>
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<td>0.4%</td>
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<td>Measured spot size</td>
<td>2 pixels</td>
<td>4 pixels</td>
<td>3 pixels</td>
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Figure 14. Specifications and Measurements Summary Table

8. REFERENCES


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