High Resolution Hyperspectral Imaging with a High Throughput Virtual Slit
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ABSTRACT

Hyperspectral imaging (HSI) device users often require both high spectral resolution, on the order of 1 nm, and high light-gathering power. A wide entrance slit assures reasonable étendue but degrades spectral resolution. Spectrometers built using High Throughput Virtual Slit™ (HTVS) technology optimize both parameters simultaneously. Two remote sensing use cases that require high spectral resolution are discussed. First, detection of atmospheric gases with intrinsically narrow absorption lines, such as hydrocarbon vapors or combustion exhaust gases such as NOx and CO2. Detecting exhaust gas species with high precision has become increasingly important in the light of recent events in the automobile industry. Second, distinguishing reflected daylight from emission spectra in the visible and NIR (VNIR) regions is most easily accomplished using the Fraunhofer absorption lines in solar spectra. While ground reflectance spectral features in the VNIR are generally quite broad, the Fraunhofer lines are narrow and provide a signature of intrinsic vs. extrinsic illumination.

The High Throughput Virtual Slit enables higher spectral resolution than is achievable with conventional spectrometers by manipulating the beam profile in pupil space. By reshaping the instrument pupil with reflective optics, HTVS-equipped instruments create a tall, narrow image profile at the exit focal plane, typically delivering 5X or better the spectral resolution achievable with a conventional design.

Keywords: Hyperspectral imaging, remote sensing, gas detection, high resolution, spectrometer design, high throughput

1. INTRODUCTION

Hyperspectral imaging is the next evolutionary step for spectroscopy. Just as grating-based monochromators using PMTs gave way to imaging spectrographs using array detectors, so will hyperspectral imaging instruments replace traditional spectrometers. Except where high speed scanning is required, as in machine vision, the additional information generated by associating images with rich spectral information is too important to neglect. Hyperspectral images consist of an array of 2D image pixels or 3D voxels associated with a spectrum at each point. Most commonly, hyperspectral images are obtained via the so-called pushbroom method, where a scene moves laterally past a tall, narrow entrance slit. A grating or prism disperses the slit image, conventionally in the horizontal direction, and an imaging optical design is used to preserve spatial information in the vertical direction, i.e. along the long axis of the slit. The dispersed slit image is then recorded with a 2D array detector. By building up a series of slit images, one can reconstruct an image of the original scene in software, using a variety of methods to display the spectral information at each pixel. Most frequently, false color images are used to highlight areas of interest. For instance, an industrial gas sensing hyperspectral imager might choose to display high concentrations of (optically invisible) ammonia in pink, or a military surveillance application might display camouflaged vehicles in a variety of contrasting colors over a realistic color scene. Similarly, an image used in precision agriculture might choose to highlight water-stressed crops to increase the contrast with healthy foliage.

While there is no standard industry terminology, hyperspectral images are typically considered to have tens or hundreds of distinct spectral channels, in contrast to multispectral images, with fewer than ten channels. The former are obtained using dispersive optics (a grating or prism), while the latter are most often obtained using optical bandpass filters. A spectral channel is defined as a wavelength range that can be distinguished from its nearest neighbors. In practice, two dispersed wavelengths can be resolved on an array detector if they are separated by at least one pixel. Hence, where imaging optics produce slit image sizes on the order of one pixel or smaller, the spectral resolution is equal to two detector pixels, and the number of spectral channels is equal to half the number of detector pixels along the horizontal axis. If the slit image width is greater than two pixels, the spectral resolution is, of course, degraded. A convenient method of measuring the spectral resolution is to illuminate the entrance slit with an intrinsically narrowband source...
such as an Hg or Ar atomic emission lamp. The spectral linewidths obtained will be determined by instrumental resolution. A Gaussian, Lorentzian or Voigt fit to these lines will produce linewidths (FWHM) that are essentially equal to the spectral resolution.

Clearly, the slit width is one of the most important parameters of a spectral imaging instrument. A wide slit allows more light into the spectrometer and decreases the number of frames required to build up a scene. At the same time, it degrades spectral resolution. Commercial instruments intended for remote sensing are typically offered with a choice of slit widths ranging from 12 to 100 µm. Doubling the slit width will increase the instrumental photon flux by 2X and the signal-to-noise ratio (SNR) by √2 when the camera performance is limited by shot noise. However, it also decreases the number of spectral channels by a factor of 2. Approaches used to overcome this tradeoff in the past include image reformatters, where the scene image at the entrance slit is deliberately made astigmatic by means of cylindrical lenses. These approaches sacrifice entrance aperture in one dimension. The High Throughput Virtual Slit is a better approach.

The HTVS has been described previously. Briefly, HTVS optics operate in ‘pupil space’, anamorphically magnifying the input aperture so that it becomes narrower in the dispersion direction and wider in the cross-dispersion direction. The net effect is to make a tall and narrow entrance slit image even taller and narrower at the exit focal plane. Hence, with a 5X slicing factor and 1:1 magnification, a 50 µm entrance slit width would be transformed to a 10 µm exit slit image width, improving spectral resolution by 5X with only negligible loss of photon flux. In this scenario, a nominal 2 mm entrance slit height would also be transformed to 10 mm, which is a good match to commercially available imaging array detectors, which are typically nearly square. The pupil slicing does not degrade the image quality and is done with all-reflective optics. When protected silver or gold mirror coatings are used, this limits reflection losses to a few % throughout the visible to MIR spectral regions.

2. HIGH RESOLUTION HYPERSPECTRAL IMAGING OF DAYLIT SCENES

Hindsight Imaging recently launched the Bilby VNIR, a compact device suitable for remote sensing. The spectral range is 400-1000 nm with spectral resolution of 1.25 nm at a 50 µm entrance slit width. Most commercial hyperspectral imaging instruments currently on the market offer much lower resolution. Many remote sensing applications rely on daylight reflected from water, vegetation, bare earth and similar terrain features. In the visible and NIR, reflectance spectral signatures are often broadband. Plant pigments, for example, have characteristic peak widths on the order of tens of nm. A high resolution spectrum of such features might appear identical to a lower resolution spectrum. Nevertheless, high resolution spectroscopy does offer benefits even with broadband spectra.

First, more spectral channels permits better analysis of complex mixtures. For example, crop plants and weeds all share similar chlorophyll and carotenoid pigments, but the precise mix of pigments leading to the visible/NIR reflectance spectrum differs by species. To resolve 10 separate components, one must have at least 10 separate spectral channels, more if noise is significant.

Second, physical changes are often manifested as spectral shifts. Significant changes in chlorophyll concentration have been characterized by red absorption shifts of less than 1 nm. A high resolution spectral imager is far more likely to resolve such a shift.

Chlorophyll fluorescence, which is indicative of plant health and productivity, is best studied with a high resolution spectrometer. Direct and reflected sunlight includes sharp absorption features called Fraunhofer lines, as shown in Figure 1.
Broadband emission sources, such as thermal objects or photosynthetic emission, lack these features. Hence, one can quantify the ratio of emission to reflection in a daylit scene by the relative strength of the Fraunhofer lines. If they are present at normal levels, then the scene lighting is entirely due to reflected sunlight. If they are completely absent, then the scene lighting must be entirely due to intrinsic photoemission. This has been described in a recent publication. A high resolution instrument enhances the detectivity of the narrow Fraunhofer lines, enabling an analyst to determine the relative levels of emitted and reflected light within a scene.

3. HIGH RESOLUTION HYPERSONAL IMAGING OF HYDROCARBON VAPORS

While absorption and reflectance spectra of terrain features are often broadband, gases usually have quite narrow absorption lines. Atmospheric gases such as water vapor, CO₂, methane and other light hydrocarbons, NOx and SOx all have well-characterized absorption spectra with multiple, narrow lines. Instrumental line broadening increases the width of narrow spectral lines at the expense of the peak intensity, so a spectrometer with 10 nm resolution will record peak intensities that are only 1/10 the intensity recorded with a 1 nm instrument. As the limit of detection of a substance is often determined by the height of a peak above the noise floor, a high resolution spectrometer will be far more sensitive to trace gases. Figures 2 and 3 below show the mid-IR absorption spectra of selected hydrocarbon vapors obtained at different spectral resolutions over the 3.1-3.6 μm region. These spectra arise from C-H stretching vibrations of the molecules in question, and could be obtained using a high resolution hyperspectral imager outfitted with an InSb detector. In Figure 2, the resolution of 3.2 nm (3 cm⁻¹) is clearly sufficient to resolve individual rovibrational peaks of methane, and much of the fine structure of ethane. The heavier hydrocarbons, in contrast, are collisionally broadened by atmospheric constituents and lack resolvable fine structure. In Figure 3, the resolution of 14 nm (13 cm⁻¹) can only partially resolve the methane peaks and the heavier hydrocarbons are more difficult to distinguish from one another due to the smearing of spectral features. The limit of detectivity of the lighter gases, as determined by the maximum absorbance, is also reduced at lower resolution. Commercial applications of high resolution imaging of hydrocarbon vapors include pipeline corridor mapping, where an instrument with chemical-level sensitivity is useful in distinguishing localized pipeline leaks consisting of mixed hydrocarbons from non-anthropogenic sources of methane such as peat bogs.
Figure 2. Higher resolution absorption spectra of selected hydrocarbon vapors.

Figure 3. Lower resolution absorption spectra of selected hydrocarbon vapors.
4. HYPERSPECTRAL IMAGING DISTINGUISHES LIGHT SOURCES

A simple demonstration of high resolution hyperspectral imaging can be done using consumer white light bulbs. These sources all appear more or less ‘white’ to the eye, with incandescent bulbs producing a ‘warmer’ light that is highest in red wavelengths while fluorescents produce a ‘cooler’ light that is enriched in the blue. Spectral analysis shows immediately obvious differences. Incandescent lights produce a smooth, featureless blackbody spectrum while LED bulbs typically have one to several diode emission bands combined with a broader phosphor emission. Compact fluorescent (CFL) bulbs have distinctive strong, narrow Hg emission lines with a phosphor. Sample images and spectra are shown in Figure 4, below. These images were obtained by translating light bulbs mounted on a stage past a lens mounted on the Bilby VNIR hyperspectral imager, acquiring data at 0.1 ms per frame. Sequential frame data were assembled to produce the images shown. Red rectangles over the white light images indicate the regions from which the spectra below were derived. Visually, the light sources appear similar, but their spectra are completely different. This application, while simplistic, indicates how hyperspectral imaging might be used in, for example, an energy audit of an office building. A telescope mounted at a distance of hundreds of meters could be arranged to scan over an image of the office windows, highlighting in false color the offices where different light sources are used.

![Figure 4](http://proceedings.spiedigitallibrary.org/proceedingsimage?doi=10.1117/12.2450866)

Figure 4. Top: Hyperspectral images of three consumer light bulbs obtained with the Bilby VNIR hyperspectral imager. The white color approximates the image as recorded by a color camera. Middle: spectra of the three light sources. Bottom: Contrasting color hyperspectral images as might be used to visually map office building windows for an energy audit.

5. CONCLUSIONS

The high throughput virtual slit is a convenient optical solution to the problem of obtaining high resolution spectra with high photon flux. Hyperspectral imaging instruments so equipped can generate more information from the same data than lower resolution instruments. While not all remote sensing problems require high spectral resolution, it is often the case that detailed resolution information becomes valuable once it becomes easy to obtain. As array detectors become smaller, cheaper and easier to use, with smaller pixels, lower noise and faster readout, imaging spectrometers too will evolve to match these characteristics. HTVS-enabled spectrometers offer enhanced resolution at the same size as conventional instruments or, alternatively, can be made much smaller than and with comparable resolution to conventional designs. Hence, they are expected to occupy an important market niche as hyperspectral imaging becomes more prevalent in solving business, security and environmental problems.
REFERENCES


[8] Data from https://secure2.pnl.gov/nsd/nsd.nsf/Welcome