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Abstract. We describe a high-throughput (5×10^{-4} cm^2 sr) imaging spectrograph that uses an echelle grating operating at a high dispersion order (24 to 43) to observe extended sources such as atmospheric airglow and diffuse proton aurora at high spectral resolution (approximately 0.02 nm). Instead of using a traditional single slit, the implementation of the instrument described here uses four (50 $\mu m \times 25$ mm) slits through which the radiation enters the spectrograph. The field of view is selected using appropriate foreoptics: the present implementation is a long, narrow configuration of 0.1×50 deg. By placing interference filters in the beam path, the instrument can simultaneously observe several spectral features located anywhere in the visible band (approximately 300 to 1000 nm) at high resolution. This design allows a single echelle grating and a single detector (a CCD in the present implementation) to view the same scene. The design is flexible; the number of slits and the slit dimensions can be tailored to the trade-offs between resolution, throughput, and number of spectral features depending upon the measurement need. While the implementation described here covers only the visible range, the use of different combinations of detector and filter sets can extend its operation to other wavelength regions. [DOI: 10.1117/1.OE.51.1.013003]

Subject terms: hyperspectral imaging; spectrographs; auroras; airglow; astronomy; multispectral imaging.

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1 Introduction

Spectral imaging, which simultaneously obtains spectral and spatial diagnostics, is now a well-established tool used for many applications including terrestrial remote sensing, planetary aeronomy, and astrophysical investigations (see, for example, the new on-line journal dedicated to spectral imaging in Ref. 1). In many of these applications, the key spectral features are known and one needs to observe multiple features simultaneously. However, they are often separated in wavelength so that, due to the limited number of available pixels on a detector, it is not possible to simultaneously observe all of the key diagnostics at the necessary spectral resolution.

As an example, consider just the emission lines of atomic oxygen in the daytime airglow. For a comprehensive understanding of the processes that produce the prominent lines, it is desirable to observe them simultaneously. These features are spread over a large wavelength range at 557.7, 630.0, 636.4, 777.4, and 844.6 nm (Ref. 2). These emissions are produced by different photochemical processes and have different altitude distributions.[3] The terrestrial magnetic field geometry and the location of the sun play an important role in the geographic distribution of their brightness. Furthermore, these emissions are also present in the aurora, where brightness, location, and extent are extremely variable with time. Each of these characteristics is an important indicator of the complex processes involving the neutral atmosphere, ionosphere, solar electromagnetic and corpuscular radiation, and the plasma population in the near-space environment. The resulting line emissions are present above the 100-km altitude regions of the sunlit terrestrial atmosphere with brightnesses of 1 to 8×10^8 photons $cm^{-2}\,s^{-1}\,sr^{-1}$. The emissions are also present in the auroral atmosphere. Just as the stars are invisible from the ground during the daytime, these emissions cannot be observed easily from the ground due to the strong background signal produced by scattered sunlight ($\sim$1 to 4×10^{12} photons $cm^{-2}\,s^{-1}\,sr^{-1}\,nm^{-1}$).

Recognizing that fainter airglow and auroral line emissions could be observed in presence of significantly bright continuum-background emission using high-resolution spectroscopy we developed a novel imaging spectrograph.[4] The high-throughput imaging echelle spectrograph (HiTIES) uses an echelle grating fed by a slit and a mosaic of bandpass interference filters to eliminate order overlap instead of a cross disperser. This optical arrangement allows simultaneous measurements of widely distributed, multiple spectral features on the same detector. HiTIES has a spectral resolution of 0.03 nm and was designed to observe approximately 5 to 20 distinct wavelength regions distributed anywhere across the visible range. HiTIES has afforded a new capability to aeronomers and has been used to address important questions including a comprehensive study of the Ring effect in the sunlit atmosphere[5] and proton aurora during twilight.[6]

A simpler version of HiTIES, called a high-resolution imaging spectrograph using an echelle grating (HIRISE), has been used extensively for ground-based airglow and auroral studies.[7] HIRISE observes a single wavelength region at a resolution of 0.012 nm and like HiTIES, it also images emissions along the slit. HIRISE has been used

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extensively to study OI 630.0-nm doublet emissions that can be used to infer physical properties of the upper atmosphere. Results from these two instruments, along with work by others, have been summarized elsewhere.[8–11] More recently, a new instrument of this family—a continuous high-resolution instrument for multiwavelength echelle spectroscopy (CHIMES)—has been developed which, with a spectral resolution of 0.015 nm, can simultaneously observe two prominent upper-atmospheric emission features (at 557.7 and 630.0 nm) in a round-the-clock continuous operating mode.[12]

We have now developed a new and versatile implementation of the same family of spectrographs. The high-throughput and multislit imaging spectrograph (HiT&MIS) uses a single echelle grating, a single CCD detector, and a set of interference filters like its predecessors. In HIRISE, an interference filter is placed at the entrance slit, which allowed only one spectral range to be recorded; in HiTIES, a mosaic of interference filters placed at appropriate location in the image plane allowed several widely spaced wavelength regions to be recorded at high spectral resolution. HiT&MIS uses multiple slits feeding the spectrograph with both a mosaic of filters as well as filters at the slits.

In this paper, we describe the design consideration and performance of the instrument. The first implementation is for ground-based spectral imaging studies of aurora. This ensures that the key emission features are observable. Furthermore, some of the emissions (hydrogen Balmer alpha and Balmer beta, $H\alpha$ and $H\beta$, respectively) require a wider spectral coverage, while others require higher spectral resolution, but a smaller wavelength coverage. Slit widths and filter combinations and their placement in HiT&MIS have been used to accommodate these disparate requirements using a single grating and detector.

2 Measurement Requirements

Characterization of the physical properties of precipitating electrons and protons in the aurora, by observing the optical emissions and their morphology, is an area of active research in solar–terrestrial relationship studies. The electron component of the precipitation has been well studied and can be well characterized using imaging spectroscopy.[13] Observations of the Doppler-shifted H emissions allow one to assess the morphology, dynamic evolution, and spectral characteristics of the source regions of the energetic protons projected onto the atmosphere in the auroral zones. Quantitative assessment of H emission brightness, incident proton mean energy, and flux and the effect of energetic H^+/H on the upper atmosphere require spectroscopic measurements of the H emission profile.[9] HiT&MIS will see its first scientific application in such a study described in Table 1: the table summarizes the key spectroscopic features that need to be measured along with the required spectral coverage and resolution. To achieve the scientific goals, all of these emissions should be observed simultaneously from the same emitting region.

While the nighttime auroral oxygen emissions do not require observations at a high spectral resolution, we plan to make observations during twilight and sunlit conditions. The auroral emissions are quite variable and require observations at a time resolution of approximately 120 s to properly follow the major emission morphologies. An important design

Table 1 Key requirements imposed on the HiT&MIS spectrograph.

Features (nm)	Required wavelength coverage (nm)	Required spectral resolution (nm)
$H\alpha$ (656.3)	≥6	≤0.1
$H\beta$ (486.1)	≥7	≤0.4
O 557.7	≥1	≤0.03
O 630.0	≥1	≤0.03
O 777.4	≥1	≤0.03
N_2^+ 427.8	≥3	≤0.1

In addition, we require that a common 0.1×50 deg field of view is probed for all spectral features and a sensitivity to detect a 20-R signal at 486.1 nm (1 R or 1 Rayleigh $\approx 8 \times 10^4$ photons $cm^{-2}\,s^{-1}\,sr^{-1}$) with approximately 120-s temporal resolution at a signal-to-noise ratio of ≥3. It should be capable of observing 1-kR 630.0-nm dayglow intensity in presence of 10-MR/nm continuum background. To be valuable, the instrument should be rugged and reliable enough to allow unattended and 24/7 continuous operation. It should also be portable so that it can be collocated with other ground-based optical and radio instruments worldwide.

requirement is the ease of changing the parameters shown in Table 1 from one investigation to another. For practical reasons, we require that the grating and CCD detector are available commercial-off-the-shelf (COTS) parts.

Conventional imaging spectrographs use a narrow and long slit: the narrow direction defines the spectral resolution while the long direction provides angular coverage. These instruments disperse spectra monotonically along a direction perpendicular to the long direction of the slit, thereby allowing a 2-D detector to simultaneously record spectrum and its variations in angular space. This technique has been and continues to be the mainstay for imaging spectroscopy applications.

Nevertheless, as it can be seen from Table 1, there are applications that require simultaneous observations of spectral features that are widely separated and require high spectral resolution. Conventional spectrographs must observe all spectral features with the same spectral resolution, as defined by the slit width and optical aberrations. This may pose a problem for some features, especially the faint ones, which, when observed at high resolution, cannot support the necessary cadence.

Determined by detector response, the HiTIES instrument[4] was designed to measure spectral features located anywhere in the visible spectral region. By utilizing an echelle system operating at a high dispersion order, it ensured that in a given order, the spectra are dispersed monotonically. However, spectra from adjacent orders overlap and produce a spectrum that combines many different orders without any discernable dispersion pattern. Using bandpass filters at the image plane ensures that selected regions on the focal plane contain the desired features and suppresses contaminating background signals.

HiTIESwas deployed near the European Incoherent Scatter (EISCAT) radar facility at Tromsł, Norway (66.4° N magnetic latitude) for a multiyear proton auroral study.[6]

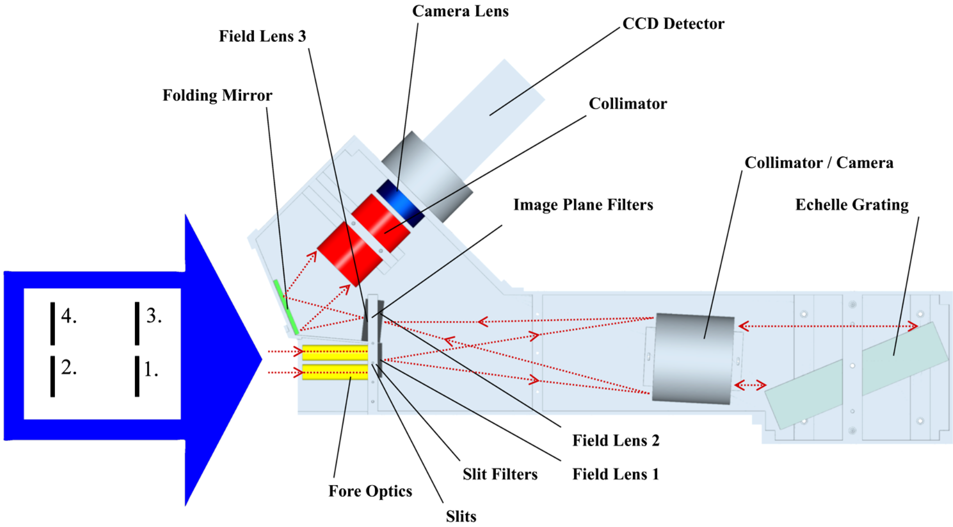

Fig. 1 Schematic representation of the HiT&MIS. The four slits, as viewed from field lens 1, are shown on the left with their designation.

While it demonstrated the capability of the instrument and resulted in significant scientific contributions, it also demonstrated the limitation of a single-slit single-objective lens system using a jury-rigged filter set arrangement (see their Fig. 4) in HiTIES for proton auroral studies.

To overcome the limitations of HiTIES, we imposed two new design requirements:

1. All spectral features of the new instrument view the same emitting region on the sky.
2. Not all features need to be observed at the same spectral resolution, but they should use the same temporal cadence.

To these, we also added the requirement that in addition to the four spectral features probed in the proton campaign,[6] two prominent and well-studied spectral lines of atomic oxygen (the "red line" at 630.0 nm and the "green line" at 557.7 nm) should be observed simultaneously in the same manner. This set of diagnostics, in combination with the instrument's spectral resolution, field of view, and sensitivity, will make the new instrument a powerful tool for aeronomers. The functional requirements for HiT&MIS are summarized in Table 1.

3 Optical Design

The optical layout for HiT&MIS is shown in Fig. 1 and the key optical components are listed in Table 2 along with their characteristics. This represents a compact implementation of the system using COTS components.

Light enters the instrument through four slits in the present configuration. The number of slits, their placement, and characteristics such as width and height can be varied depending upon the measurement need. Each slit is fitted with a filter (see Table 3) that in combination with the mosaic filters placed at the image plane (see Fig. 1) determines the spectral feature that will be recorded by the CCD detector.

Light from the slits selected by the filters passes through a field lens and a collimator and isdispersed by the flat echelle grating in a near-Littrow configuration. The diffracted light is imaged by the same collimating lens, now acting as a camera lens, in a manner analogous to the Ebert-Fastie spectrometer,[14] onto an image plane, where a mosaic of interference filters further selects the spectral features to be recorded by the detector.

After passing through a field lens, the light is redirected by a fold mirror for packaging purposes only. A set of collimator and camera lenses is used to reimage the scene

Table 2 The main components of HiT&MIS and their properties listed in the order a photon travels from the sky to the detector.

Component	Characteristics
Fore optic	Four 8-mm-diameter, $F/3.5$ lenses—one per slit.
Entrance slits	50 $\mu m \times 25$ mm. There are four slits. The width is selectable (25 to 200 μm). The optical properties of the filters are described in Table 3.
Field lens 1	50×50 mm, 500-mm focal length plano-convex.
Collimator/ camera	100-mm diameter, 400-mm focal length achromat.
Grating	Size: 110×220 mm; ruled area: 102×204 mm; ruling density: 98.76 lines/mm; blaze angle: 65.5 deg; angle of incidences: 69.3 ± 1.5 deg.
Field lens 2	50×50 mm, 500-mm focal length plano-convex.
Field lens 3	50×50 mm, 200-mm focal length plano-convex.
Fold mirror	76×102 mm
Collimator	50-mm diameter, 210-mm focal length Cooke triplet.
Camera lens	50-mm diameter, F/0.95
Detector	Princeton Instruments PIXIS 1024B with an e2v CCD47-10 1024×1024 pixels, 13.3-mm square chip with a typical rms readout noise of 3.0 electrons/pixel at 100-kHz sampling frequency and a typical dark current of 0.001 electrons/s/pixel

Table 3 Characteristics of the slit filters for this implementation of HiT&MIS that were optimized for auroral studies.

Slit	Filter type	Bandpass (nm)	Peak transmission (%)
1	Schott BG3	280 to 460	75
		710 to 1100	90
2	GG495 and	>495	91
	700 FL07	<700	77
3	OG 590	>590	91
4	550 FL07	<550	85

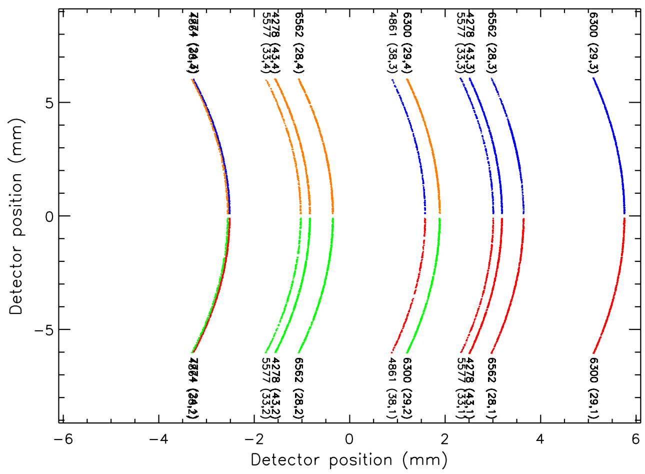

Fig. 2 Ray trace calculation for HiT&MIS showing prominent airglow features and the effects of slit curvature on the photon positions in the image plane. Wavelengths of the features are shown from the four slits. The numbers inside the parenthesis indicate the diffraction order and the slit number, respectively. Without filters the spectra from different orders overlap and are quite confusing as seen in the two leftmost features: the 486.1-nm line in the 34th order and the 777.4-nm line in the 24th order essentially overlap one another.

at the image plane on to a 13×13 mm CCD array with 1024×1024 pixels.

4 Ray Trace Calculations

To examine the performance of the spectrograph, we conducted a ray trace simulation. The complications posed by the use of a long-slit echelle spectrograph at high diffraction orders are well understood.[4,7] The performance of the as-built instrument was very similar to what was predicted by these computations.[4] Figure 2 shows the additional complications of feeding such a system with multiple slits. First, like HiTIES[4] and HIRISE,[5] dispersed spectra from straight slits are curved. Curved slits can be used to straighten the slit images, however, this will result in a complex sampling of the scene.

Each of the four slits produces a spectrum at the image plane (see Fig. 2). The four slits are a pair of slits separated by 22 mm and stacked atop another pair. In the current implementation each slit has identical dimensions (50 $\mu m \times$ 25 mm); however, the design is completely flexible and each slit can easily use different widths (resulting in different spectral resolution) and lengths.

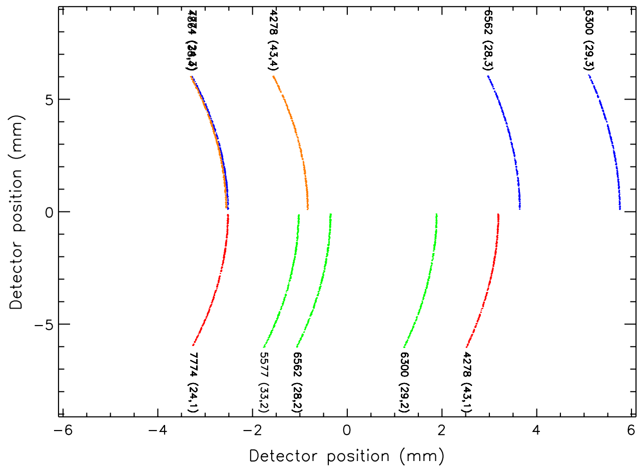

Fig. 3 Same as Fig. 2, but with the slit filters (Table 3) included. The spectra are more distinct, but there is still significant overlap—notably the 486.1 and 777.4-nm features in the upper left quadrant.

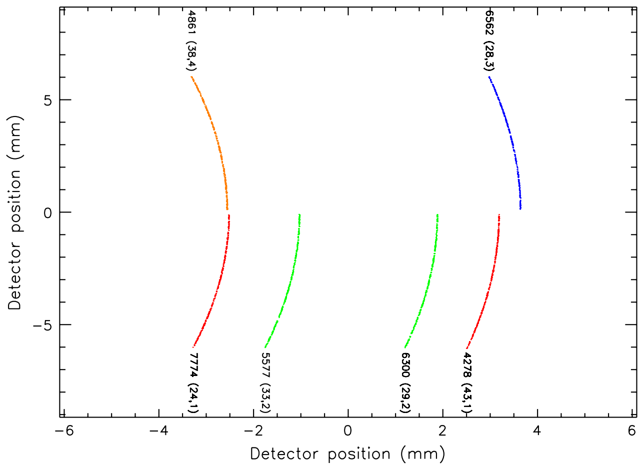

Fig. 4 Spectral features recorded with both slit and image plane filters in place. The top half of the detector will record two prominent atomic hydrogen features present in proton aurorae. The four bottom panels record atomic oxygen and molecular nitrogen emissions that can be used to infer key physical parameters of electron aurorae. The ability to spectrally image all these emission features simultaneously at high resolution will open up new capabilities in auroral research.

The filters placed at the slits (Table 3) eliminate some of the order overlaps. This configuration is similar to HIRISE[7] where a selected spectral feature is allowed to enter the instrument. HiT&MIS is significantly more versatile. The filters for HiT&MIS were chosen to provide a selected bandpass through each of the four slits. The filters pass selected spectral features at the focal plane as shown in Fig. 3. In addition, a mosaic of interference filters with 10- to 20-nm bandpass, similar to that used in HiTIES,[4] is used for this implementation resulting in the arrangement of the spectral features in the focal plane as shown in Fig. 4.

5 Sensitivity Estimation

We have estimated the expected sensitivity of the instrument using reasonable values of optical efficiency, which includes

Table 4 Sensitivity of the HiT&MIS instrument.

Slit width	Solid angle (sr)	Grasp (cm^2 sr)	Spectral resolution at 480 nm (nm)	Sensitivity (counts s^{-1} R^{-1})
50 μm; 0.1 deg	1.46×10^{-3}	5.08×10^{-4}	0.014	5.3
100 μm; 0.2 deg	2.91×10^{-3}	1.02×10^{-3}	0.028	10.6
500 μm; 1 deg	1.46×10^{-2}	5.08×10^{-3}	0.14	52.8
1000 μm; 2 deg	2.91×10^{-2}	1.02×10^{-2}	0.28	105.6

filter and lens transmission efficiencies and reflectivity (90%) of the fold mirror and the grating as well as the grating blaze efficiency (80%). We also used a value of 80% for the CCD quantum detection efficiency. The results of our sensitivity calculations are summarized in Table 4.

6 Summary

We have described a versatile high-resolution (0.014 to 0.28 nm FWHM) and high-sensitivity (5 to 100 counts s^{-1} R^{-1} depending on the selected spectral resolution) imaging spectrograph for studies of extended sources such as the aurora. It uses an echelle grating operating at a high diffraction order (24 to 43) in a near-Littrow configuration. Light enters the instrument through four slits, each with its own filter, which in combination with a mosaic of filters located at the image plane, select desired spectral features and separate overlapping spectral orders. The spectra are recorded by a CCD detector.

The slit dimensions and filters can be changed to allow a different combination of spectral features as well as different sensitivity and bandwidth combinations. This feature makes HiT&MIS an easily reconfigurable, highly powerful, and very flexible optical tool.

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Olli-Pekka Jokiaho received his MPhys in space science at the University of Southampton, U.K., and completed a doctoral degree in 2009. Since 2010, he has been working at the Center for Space Physics at Boston University as a research scholar. His research interests include spectral modeling of ionospheric optical emissions and spectrograph design.

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Timothy Cook specializes in developing novel instrumentation and data analysis techniques. He is currently working on instruments to study phenomena ranging from the formation of the structure of the universe to the atmospheres and environments of planets around nearby stars to the structure and carbon content of forests on earth. His primary research thrust is the use of suborbital sounding rockets to study astrophysical phenomenon.

Jason Martel graduated with a BS in mechanical engineering from Boston University. He designs, analyzes, and oversees manufacturing of land and space research instruments. His design focus is on enclosures and mechanical supports for the optical elements used in these instruments. His current projects include a LIDAR instrument that measures densities of leaves and tress within forests, as well as a UV sounding rocket measuring metallicity and radiation effects on interstellar dust.

Marina Galand is currently a senior lecturer at Imperial College London, UK. She received a PhD in space physics in France in 1996. She then moved to the U.S. where she carried out research, primarily on terrestrial proton aurora, for 10 years at NCAR, NOAA, and Boston University. She moved to London six years ago where her prime research focus widened to planetary atmospheres in close relation to space missions. She has been investigating solar and auroral particle energy deposition in atmospheres of bodies throughout the solar system, using sophisticated state-of-the-art kinetic and fluid models that she developed and adapted to new environments. She has published more than 45 scientific papers in major peer-reviewed international journals, 17 of which as first author, and written and contributed to several book chapters. Her work has been awarded the Zeldovich Medal.