Applications of Optical Spectrographs for Passive Remote Sensing of Upper Atmosphere

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1. Introduction:
Several dynamically varying phenomena occur in the Earth’s upper atmosphere in response to the energy inputs from above (solar radiation, particle precipitation, etc.) and from below (gravity waves). In the low and equatorial latitudes, strong electrodynamically coupled phenomena occur owing to the unique geometry of the magnetic field lines. In the high latitudes the upper atmosphere is electrically coupled to the magnetospheric currents. The coupling between various latitudinal locations becomes more pronounced during magnetic storms and substorms when there is a significant transfer of energy and momentum from the high- to the low-latitudes via traveling ionospheric disturbances, gravity waves, etc.

One of the important and useful means of investigating upper atmospheric dynamics is the measurement of optical airglow/auroral emissions. Different emissions originate at different altitudes depending on the number densities of the reactants at the given altitude and on the energies required for the individual reactions. Hence, optical emissions from atomic and molecular constituents of the earth’s atmosphere yield useful information on the behavior of the altitude of their origin (such as the neutral temperature, winds, gravity waves, etc.). Of the various modes of airglow measurements from different platforms, ground based measurements provide information on the temporal evolution of a phenomena over a fixed site and ideally compliment the global measurements provided by satellite-borne experiments. Also, ground-based measurements can continuously employ larger integration times to observe weak emissions. For these reasons, there have been many innovations made in the ground-based airglow observational techniques.

Extensive measurements of the nighttime airglow (nightglow) have been carried out from spaceborne and ground-based platforms since several decades. Nighttime measurements of integrated airglow emission rates at various wavelengths have been used to infer thermospheric behavior under varying geophysical conditions from different latitudes. Fabry-Perot scanning spectrometers have been used to obtain thermospheric neutral winds and temperatures by measuring OI 630.0 nm emission line profile (for e.g., Shepherd et al., 1978; Hernandez, 1982; Biondi et al., 1985; Meriwether et al., 1986; Sridharan et al., 1991). These techniques essentially used a central aperture scanning method. Observations from different regions of the sky were accomplished by a scan mirror, which results in low temporal resolution. With the availability of two-dimensional detectors, Fabry-Perot fringes are now imaged to obtain high-resolution wind and temperature measurements from a wide field-of-view (fov) (e.g., Sivjee et al., 1980; Ress and Greenway, 1983; Sekar et al., 1993; Sridharan et al., 1993; Biondi et al., 1995; Conde and Smith, 1997). Using an all-sky lens and a filter one can obtain emissions from different wavelengths and so for multiple wavelength measurements a filter wheel arrangement is needed. This technique has resulted in measurements of plasma depletions from low-latitudes, gravity
wave propagations in various emissions, plasma patches in high latitudes, etc. (e.g., Mende et al., 1977; Mendillo and Baumgardner, 1982; Weber et al., 1984; Taylor et al., 1995).

In contrast, there have been only a handful of daytime measurements from the ground, mainly due to the difficulty in removing the strong solar background continuum that is at least three orders of magnitude larger as compared to the dayglow/daytime auroral emissions (solar zenith angle, SZA < 90°) even at 0.01 nm spectral resolution. Globally, on an average, 66% of a given 24 hour period consists of daytime/twilighttime. There have been only a few satellite-based measurements of visible airglow emissions during daytime (Hays et al., 1978; Shepherd et al., 1993). As pointed above, information on the temporal evolution of the emissions at a given location are possible only by ground-based measurements. Hence, there has always been a need for newer techniques for ground-based measurements of dayglow emissions (see review by Chakrabarti, 1998). Earlier spectral scanning polarimeter (Noxon and Goody, 1962), poly-etalon Fabry – Perot interferometers (e.g., Bens et al., 1965; Barmore, 1977; Coeks et al., 1980; Greet et al., 1989; Rees et al., 2000) and a single Fabry–Perot etalon in conjunction with a novel mask system (Narayanan et al., 1989; Pallam Raju et al., 1995; Sridharan et al., 1993, 1998) have been employed to measure the dayglow emission rates. The potential science yield of daytime measurements have been discussed extensively during two CEDAR Workshops in 1997 convened by J. Baumgardner and R. Smith and in 2002 convened by D. Pallamraju and M. Conde. Moreover, the topic of “Daytime airglow studies of ionospheric structures” has been recognized as being among the top seven highlighted topics of research by the CEDAR Steering committee in 2003.

In this overview, we will briefly discuss the scientific contributions to advancements in our understanding of upper atmospheric phenomena by optical spectrographs developed at Boston University (BU). These spectrographs use an Echelle grating in combination with broadband interference filters to obtain high spectral resolution measurements of nighttime, twilighttime and daytime optical airglow emissions. These instruments are called the High Throughput Imaging Echelle Spectrograph (HiTIES) for nighttime/twilighttime measurements (Chakrabarti et al., 2001) and High-Resolution Imaging Spectrograph using Echelle grating (HIRISE), for twilighttime/daytime airglow emission measurements (Pallamraju et al., 2002). Using these techniques different noncontiguous wavelengths are measured simultaneously over a wide fov. Towards the end of this review we will also discuss the potential future developments that are being planned for these spectrographs.

**Figure 1** Schematic of HiTIES spectrograph. At its heart are an Echelle grating and a multi-panel mosaic filter that replaces conventional cross dispersers found in astronomical Echelle systems. Other components include interchangeable fore-optics, folding mirrors, collimators, field and imaging lenses, and a two-dimensional imaging detector.
2. Uniqueness of BU Spectrographs:

Traditional imaging spectrographs disperse the spectrum in wavelength in a monotonically increasing or decreasing order. This works well when the instrument parameters are such that the entire spectral region of interest can be accommodated by all the pixels available on the detector. However, when it is required to record the spectral lines in 4000 – 10000 Å wavelength region simultaneously with, for example, 0.3 Å resolution, – one would need at least 40,000 detector pixels in one direction (assuming that at least two detector pixels are needed for sampling a spectral bin with a dispersion of 0.15 Å pix\(^{-1}\)). As of now no detector of this kind exists. So, to overcome this difficulty, we use Echelle gratings that operate in high diffraction orders (20 to 100). When using high orders, spectra from a number of different orders will be diffracted in the same direction, which results in order overlap as can be seen by the grating equation:

\[ m\lambda = d (\sin \alpha + \sin \beta) \ldots \ldots \text{Equation 1} \]

where \( m \) is the diffraction order, \( \lambda \) is the operating wavelength, \( d \) is the groove spacing, and \( \alpha \) and \( \beta \) are the incident and diffracted angles, respectively. It can be seen that \textit{equation 1} can be satisfied by different sets of \( \lambda \)s of different orders for the same \( \alpha \) and \( \beta \) (when \( m_1 \lambda_1 = m_2 \lambda_2 \)). In the BU spectrographs we use this problem of order overlap to our advantage. Instead of using traditional cross-dispersers as it is done in Astronomical applications, we use a mosaic of interference filters, one filter for each of the spectral band.

3. High Throughput Imaging Echelle Spectrograph (HiTIES):

HiTIES is a high-throughput imaging spectrograph that is capable of making simultaneous measurements of atmospheric emissions in 3900 Å – 8000 Å spectral region over a large fov (Chakrabarti et al., 2001). Figure 1 and Figure 2 show the schematic of HiTIES instrument and a sample spectral image obtained at multiple emissions from Sondrestromfjord, Greenland. Experiments from Tromso, Norway using HiTIES yielded unambiguous measurements of proton aurora (Galand et al., 2004).

4. High Resolution Imaging Spectrograph using Echelle grating (HIRISE):

The dispersion of HiTIES has been increased by about a factor of four in order to be able to make daytime airglow emission measurements. This instrument, called the High Resolution Imaging Spectrograph using Echelle grating, is a long-slit (40 mm) high spectral-resolution (0.12Å) imaging spectrograph that is capable of obtaining daytime airglow emissions in the presence of the bright solar background continuum. HIRISE uses an interference filter, (placed behind the slit) for order separation, which allows only about 10 nm spectral bandwidth of light, an Echelle grating as the disperser element, and a 1k x 1k pixels back-thinned CCD detector to record the high resolution spectrum. Figure 3 shows the schematic of HIIRSE. The fov can be varied from \( 8^\circ \) to \( 180^\circ \) by changing the objective lens in the front.
5. Dayglow Emission Extraction:
HIRISE instrumentation and the data analysis procedure have been described in detail earlier (Pallamraju et al., 2000, 2002) and hence only a brief description is presented here. Daytime airglow emissions are obtained by comparing the solar spectrum to the sky spectrum. The contributions to the sky spectra differ from the solar spectra in terms of the presence of (a) atmospheric emissions, (b) atmospheric scattering or the Ring effect and (c) atmospheric absorptions (Telluric lines). As the 630.0 nm emission region does not have any Telluric line, the difference between the scaled solar and the sky spectra yields contributions due to the airglow/auroral emissions and the Ring effect. By properly accounting for the Ring effect one can obtain the 630.0 nm daytime airglow/auroral contributions (Pallamraju et al., 2000, 2002) as depicted in Figure 4.

We will now briefly discuss the scientific results that we obtained using HIRISE from different latitudes. Firstly, we will briefly discuss the controversies surrounding the Ring effect and show how the HIRISE measurements resolved them.

6. Multiwavelength investigation on the Ring effect:
Ring effect refers to the ‘filling-in’ of the Fraunhofer absorption lines in the day sky spectrum as compared to the solar spectrum. As most of the atmospheric emissions occur in Fraunhofer absorption regions, it is essential to ascertain the Ring effect contribution to obtain
the emission rates during daytime. Rotational Raman scattering is believed to be the main cause for this excess in the sky spectrum. It is important to take proper account of this effect as it otherwise results in overestimating the dayglow emission intensities and in underestimating the number densities of atmospheric trace gases.

Previous ground based measurements of the Ring effect showed inconsistent correlations, both with SZA and wavelength. Pavlov et al., (1973), Barmore (1975), and Harrison (1976) showed an increase in the fractional Ring effect (FRE) \([FRE = \frac{\text{Ring Effect contribution}}{\text{Background Contribution} + \text{Ring Effect Contribution}}]\) with SZA by a factor of around 2 to 3 from a SZA of 30° to 90°. However, Noxon and Goody (1965) and Harrison and Kendall (1974) showed a decrease in the Ring effect by a factor of 2 with SZA (in similar SZA range). Conde et al., (1992) found the FRE at 589.3 nm to remain nearly constant during the day followed by a steep rise (by a factor of 6) around twilight time. With regard to the variability in wavelength, Noxon and Goody, (1965) and Pavlov et al., (1973) showed a decrease of FRE with wavelength while Harrison and Kendall (1974) and Chanin (1975) showed an increase in the FRE with wavelength. In all the above measurements the instrument resolutions were poorer (≈0.2-0.4 nm vs. 0.012 nm) than the present experiment (except for Chanin (1975) and Conde et al., (1992)) and were carried out at most four wavelengths. Using HIRISE we carried out simultaneous measurements at 11 wavelengths from three distinctly different spectral regions to offer a plausible explanation to the existing controversies by bringing out the behavior of the Ring effect variability.

Our studies revealed that the Ring effect depends primarily on the strength (normalized depth x half width) of the Fraunhofer line irrespective of the SZA or wavelength (see Figure 5). However as the linear fits (in Figure 5) show, there seems to be an increase in the FRE (between 1-15%), towards shorter wavelengths depending on the absorption line strength. The results from our study also seem to offer a plausible explanation to the controversies in the Ring effect variation with wavelength. For example, if the absorption line strength is not taken into account, one could wrongly conclude that the FRE increases with wavelength, if one measures only two wavelengths (say 428.74 nm and 558.67 nm), which are dissimilar in their absorption line strengths. Also, our results indicate that in estimating the intensities of dayglow emissions that emanate in a Fraunhofer absorption region, care should be taken in accounting for the Ring effect contribution at this region by considering the Ring effect contribution from an absorption region that is close to and similar in strength to the Fraunhofer absorption region at the emission wavelength.

![Figure 5 Dependence of Ring effect on the strength of the Fraunhofer Absorption line. FRE is shown as a function of absorption line strength. It can be seen that absorption line strength has a greater control than either the wavelength or the SZA. The vertical spread in the data points at each wavelength show the variations associated with SZA.](image)
7. **HIRISE measurements from Low-Latitudes:**
The low- and equatorial- magnetic latitudes of the Earth present a unique magnetic field geometry. The interactions initiated by the motion of the neutral winds across the horizontal magnetic field lines over the magnetic equator results in several equatorial phenomena namely, the Equatorial Electrojet (EEJ), Appleton Anomaly (or Equatorial Ionization Anomaly), Equatorial Temperature and Wind Anomaly (ETWA), and Equatorial Spread-F (ESF) to name a few. All these phenomena show seasonal, solar cycle and magnetic activity dependence and are coupled to one another, in the sense that, the daytime EEJ drives the Appleton anomaly by creating two crests of ionization on either side of the magnetic equator. These enhanced ionization crests in turn alter the wind flow creating centers of excess temperature referred to as the ETWA. These ionization crests and the excess temperature therein become sources for the generation of cells of meridional winds that affect the occurrence of the ESF in the nighttime (Devasia et al., 2002; Jyoti et al., 2004). The ESF generated irregularities span scale-lengths over seven orders of magnitudes and affect radio communication over a wide range of frequencies. Although the ESF occurrence has been discovered over six decades ago, understanding of its day-to-day variability remains elusive till this day. Even though there are many factors that affect the ESF-triggers at the ESF onset time, we believe that the daytime ionosphere-thermosphere system prepares the equatorial ionosphere in making the background conditions conducive for triggering the ESF. The large-scale phenomenon in the low latitudes is the development of the Appleton Anomaly, which shows day-to-day variability in its strength and extent of development. So, understanding its day-to-day dynamics could provide crucial precursors to the nighttime ESF (Raghavarao et al., 1988, Sridharan et al., 1994). This effect was also supported by the TEC measurements at sunset over the American longitudes by Mendillo et al., (2001) and Valladares et al., (2001).

Using HIRISE we carried out daytime OI 630.0 nm measurements from Carmen Alto, Chile (23.1°S, 70.6° W; 10.6° dip lat.) to understand this dynamics in the American sector. The sources of OI 630.0 nm daytime emissions are (i) Photoelectron impact on O, (ii) Photodissociation of $O_2$ and (iii) Dissociative Recombination of $O_2^+$. The first two processes are dependent on the SZA, and hence they are not expected to show any small-scale variability that the oxygen dayglow emission displays (see figures 6 – 8 below). By accounting for SZA contributions in the red line (OI 630.0 nm) dayglow, we can retrieve the small- and long-period wave structure of the upper atmosphere.

**7.1 Low-latitude OI 630.0 nm dayglow behavior on Quiet Days:**
Figure 6 and Figure 7 show typical examples of the dynamical component in the dayglow on two quiet days (5 and 7 November 2001) with $<Ap>$
of 21 and 19. The slit of HIRISE was oriented along the magnetic meridian. Using the imaging property of HIRISE one can map the emissions observed on different regions of the detector to different latitudes in the sky assuming a 230 km altitude for the dayglow emission. One can notice a clear difference in their dynamical variation. On the 5th a peak was seen that was centered at 13 LT at 9° Mag. Lat, while on the 7th the peak emissions were observed around 13 LT but much farther in south at 12° Mag. Lat. This difference in location of the peak is most probably due to stronger Appleton anomaly development on the 7th. Jicamarca digisonde data showed the presence of ESF on the 7th and absence of ESF echoes on the 5th (Pallamraju et al., 2004b). During that campaign, out of all the days of dayglow data there were only 2 days without ESF while all the rest (more than 30) were ESF days. They all typically show similar behavior in the development of the Appleton anomaly as seen in the daytime emissions on the 7th. All the days show wave activities of different periodicities. Further investigations are currently underway to characterize the behavior of the wave-activity of the upper atmosphere on different days.

7.2 Low-latitude OI 630.0 nm dayglow behavior on magnetically disturbed days:
During geomagnetic disturbances the particle energy inputs over the high latitudes can be larger by a factor of more than an order of magnitude than the solar extreme ultraviolet radiation at the equator (Mayr et al., 1978). Mayr et al., (1978) proposed a circulation mechanism by which the neutrals from the high latitudes are transported to the lower latitudes during storm time due to winds produced by intense Joule heating. This heating also causes an upwelling of the neutral species over the auroral oval, which generates a large wave that is capable of propagating to the magnetic equator in a few hours (Mayr et al., 1978; Prolss, 1993). There are ample evidences of an increase in the neutral temperature and winds at low latitudes during magnetic storms. Simulation results show that the Traveling Atmospheric Dynamics (TADs) launched in northern and southern polar regions during magnetic storms propagate towards low latitudes at high speeds (about 670 ms\(^{-1}\) at 260 km), causing thermospheric density increase at low latitudes due to compression and compressional
heating of the thermospheric gas (Fujiwara et al., 1996). Wind Imaging Interferometer (WINDII) on board the Upper Atmospheric Research Satellite (UARS) measured winds of around 650 ms\(^{-1}\) at 200 km for a storm whose \(K_p\) value was 7.7 (Zhang and Shepherd, 2000).

The HIRISE redline measurements from Carmen Alto, Chile on a magnetically disturbed day showed first ground-based evidence of redistribution in neutral composition from high- to low-latitudes. Figure 8 shows the dayglow data on 6 November 2001 when the Dst was as low as – 300 nT and <Ap> was 192. Notice the sharp rise in the emissions during the morning hours (0530 – 0830 LT), which are 4 – 5 times larger than the emissions of the dynamical component on quiet days (see Figure 6 and Figure 7). The duration of morning rise is larger in 9\(^\circ\) – 13.5\(^\circ\) Mag. Lat. compared to the duration of increase in 7\(^\circ\) – 9\(^\circ\) Mag. Lat. Emission enhancements are also seen at around 12\(^\circ\) and 9\(^\circ\) Mag. Lat. at 1230 LT and 1330 LT, respectively, most likely due to the propagation of neutral species from high- to low-latitudes. The arrow indicates a possible direction of the phase propagation of the neutral species from high- to low-latitudes. The contribution of the dynamical component is largest on this day compared to quiet days (shown in Figure 6 and Figure 7) possibly due to the presence of comparatively larger neutral densities that are redistributed by the magnetic storm effects (Pallamraju et al., 2004b).

8. HRISE measurements from Mid-Latitudes:

HIRISE has been regularly making daytime redline OI 630.0 nm emission measurements since April 2003 from Boston University (42.2\(^\circ\) N, 71\(^\circ\) W; 48.3\(^\circ\) Mag lat.) to investigate the seasonal and the magnetic activity effects of the mid-latitude thermosphere. In response to the 30 October 2003 geomagnetic storm HIRISE recorded the first daytime aurora over Boston in OI 630.0 nm emissions. The auroral emissions were so intense that they filled the Fraunhofer absorption line and stood out as a bright emission line in the raw spectral images of HIRISE (Figure 9). The SZA during that time was 74\(^\circ\) and the solar background continuum was 4MRÅ\(^{-1}\). These daytime emissions have been estimated to be as high as 38 KR (Pallamraju and Chakrabarti, 2004).
9. HIRISE measurements from High-Latitudes:

Auroral emissions are the signatures of the complex magnetospheric and ionospheric interactions that take place over high-latitude upper atmosphere. From measurements using satellite-and rocket-borne instruments, we know that the occurrence morphology and characteristics of the daytime auroral emissions are different from those of the nighttime (Meng, 1981; Sivjee, 1983; Newell et al., 1996; Sandholt and Farrugia, 1999). A satellite-based statistical study has reported that the frequently occurring discrete auroras in the night are suppressed in daytime (Newell et al., 1996). Moreover, the large-scale high-latitude plasma density structures, or the polar cap patches that are potentially capable of affecting the satellite radio communication systems, are formed in the daytime cusp region, especially when the cusp is sunlit (Weber et al., 1984). Due to lack of observations, an unknown aspect of the high-latitude aeronomy is the conjugacy in auroral occurrence. Past observations have been restricted to only a few days during the equinox periods when there is simultaneous darkness over conjugate points on the globe. Being able to observe sunlit aurora in the summer hemisphere conjugate point would yield enormous information, not only on the differences in daytime versus dayside auroral occurrences, but also in a comprehensive understanding of the daytime aurora. We initiated observations from high-latitude to investigate some of the above mentioned science issues from Sondrestromfjord Incoherent Scatter Radar (ISR) facility, Kangerlussuaq (67° N, 51° W; 74.5° N Mag. Lat.) and Qaanaaq (77.5° N, 69.5° W) in Greenland.

9.1 Observations of Auroral Arcs in OI 630.0 nm daytime emissions:

HIRISE observations from Sondrestromfjord on 25 January 1999 with its slit oriented in the magnetic meridian revealed a strong enhancement in emission towards north of Sondrestrom. Simultaneous ISR elevation scan data were also available, which confirmed the presence of a field-aligned arc towards the north in one of its scans (Figure 10). Figure 11 shows electron densities at 200 km altitude derived from a series of such meridional scans for the duration of optical data. The bottom panel of Figure 11 shows a contour plot of the measured OI 630.0 nm daytime/twilighttime emission rates obtained by HIRISE. The plot shows emission enhancement (shown in red and white) in optical measurements at the same time and location as electron
density enhancement seen in top panel of this figure clearly indicating optical response to daytime auroral arc (Pallamraju et al., 2001).

9.2 First ground-based observations of daytime cusp and F-region auroral precipitation:

The high-latitude edge of the auroral oval defines the transition from closed to open magnetic field lines in Earth’s magnetosphere-ionosphere (M-I) system. The dayside neutral line between the open and the closed field lines defined as the magnetic cusp and is the region through which plasma from the Sun can have direct access into Earth’s upper atmosphere (e.g., Shepherd, 1979; Smith and Lockwood, 1996). On a regional scale, persistent structured electron temperature enhancements, measured coincident with unstructured F-region electron density, have been related to cusplike precipitation (Doe et al., 2001). Most of our current understanding on the optical response of the cusp aurora comes from observations made when the cusp is in darkness, which occurs only near solstice at a few locations. During sunlit periods, however, as there are contrasting changes brought about in ionization, conductivities, neutral densities and temperatures, it is not known how this most dynamic region of the Earth’s upper atmosphere manifests in the optical emissions. Optically, prior studies have characterized the cusp location as the region where the ratio of low-energy 630 nm emissions to high-energy emission (427.8 or 557.7 nm) is on the order of 3 or more (Eather and Mende, 1972; Shepherd, 1979; Rodger et al., 1995). The magnetic latitude of Sondrestrom (74.5°N) makes it a site with high probability of being directly under the magnetic cusp near magnetic noon.

Figure 12 shows the red line emissions at various elevation angles (measured from the North) along a magnetic meridian (333° azimuth) that was chosen to coincide with the ISR meridional scans from Sondrestromfjord on 21 January 2001. HIRISE images were integrated for 5 minutes, binned at an angular resolution of 10° (8–20 rows of data from each image were coadded depending on the elevation angle of the 1 x 8 on-the-chip-binned image) in order to increase the signal-to-noise ratio, SNR, (the

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**Figure 12** HIRISE measurements of cusp and F-region arc emissions on 21 January 2001 along the magnetic meridian from Sondrestromfjord (74.5° Mag. Lat). Emissions during time interval I (blue) show daytime cusplike/magnetosheath precipitation at an elevation angle of 112° with a sharp equatorward boundary. Emissions during II (magenta) and III (green) correspond to contributions from poleward moving aurora and to the equatorward movement of F-region auroral arcs as substantiated by the ISR data.
measurement uncertainties vary from 3% to 18%). The dashed black lines in this figure (before 1325 and after 1754 UT) correspond to twilighttime (SZA > 90°) 630 nm airglow emissions, while the rest of the data is obtained during daytime. During the time interval I (1330–1518 UT, in blue) column emission rates along the 112° elevation angle (22° south of zenith) increased gradually from around 1,200 R to 3,200 R over a dayglow background of around 800 R and showed a sharp southward (equatorward) boundary in the emissions. During this period the emissions northward and southward of this elevation angle do not show any such increase in brightness. We believe this is a clear signature of cusplike precipitation. After 1518 UT, the peak in the emission during interval II (magenta) shifts poleward indicating a poleward moving auroral form until 1542 UT. At the end of interval II, a southward motion in the emissions is observed during interval III (green) until 1745 UT, which is coincident with the movement of an F-region auroral arc (not shown here) (Pallamraju et al., 2004a).

Coordinated \( N_e \) and \( T_e \) measurements were made by scanning the ISR along the magnetic meridian from 1230 to 1454 UT followed by alternating scans tipped 25° to the West and East of the meridional plane from 1457 to 1801 UT. Figure 13 shows the OI 630.0 nm emissions modeled using the ISR measured \( N_e \) and \( T_e \) as inputs. Notice the similarity of these plots with the HIRISE measured cusplike emissions (during interval I) showing a confined enhancement region with a sharp equatorward boundary. The purple and orange plots representing model emissions along the scans tipped 25° towards East and West of the magnetic meridian show signatures of poleward moving auroral forms (during interval II) followed by the equatorward movement of F-region auroral arcs during interval III as indicated in Figure 12.

We believe that these are the first unambiguous measurements of the magnetospheric cusp in the daytime OI 630.0 nm emissions ever made by a ground-based instrument.

10. Future Scope for Technical and Scientific Advancements using Imaging spectrographs:
So far, we have briefly highlighted a few of the many results obtained by the high-resolution optical spectrographs. In order to further advance our understanding of the upper atmospheric phenomena several technical advancements are being planned. They are briefly elucidated below:

Figure 13 Model red line emissions obtained for 21 January 2001 using the ISR-measured \( N_e \), \( T_e \) and MSIS neutral densities as inputs. The blue lines are model estimates in a view geometry similar to the HIRISE measurements. Notice the similarity of these model emissions with those shown in Figure 12.
10.1 Multiple Wavelength Daytime Emission Measurements:
Presently the HIRISE spectrograph is capable of making multiple wavelength measurements over a small fov. In the present set-up we can place a ‘mosaic’ filter orthogonal to the slit so that different sections of the image correspond to different wavelengths as shown in Figure 2 as obtained by HiTIES. When we increase the fov these image will correspond to different spatial locations. In order to obtain multiple wavelength information from a large fov, it is required that we place this ‘mosaic’ filter in a direction normal to the slit. This is what is done in the HiTIES for nighttime and twilighttime measurements. Similarly, to achieve this in daytime, proper choice of Echelle grating and a critical placement of the optical components are required for the choice of wavelengths to be measured. For the daytime studies we have designed a multi-wavelength spectrograph consisting of OI 557.7 nm, OI 777.4 nm and OI 630.0 nm emissions. The 557.7 nm and 777.4 nm emissions originate below (~100 km) and above (~300 km) of the red line (630.0 nm) emission (~230 km) in the daytime. Therefore, such a spectrograph will be capable of providing information on the vertical coupling of waves in the upper atmosphere during daytime, which has enormous applications at all latitudes.

10.2 All-sky maps of Daytime Volume Emission Rates:
Presently HIRISE obtains all-sky information along the slit orientation. We plan to rotate the slit orientation to obtain information from different spatial locations. Such information could be employed to obtain 2-D maps of daytime optical emissions to investigate the wave propagations in different directions during both quiet and magnetically disturbed conditions from different latitudes. Once the multi-wavelength instrument is developed, we plan on augmenting its capability to obtain 2-D all-sky maps. The scientific yield of such a capability will greatly advance our current understanding by providing experimental data on the atmospheric dynamics at multiple altitudes.

10.3 Simultaneous measurements from a HIRISE Chain:
As HIRISE is capable of making round-the-clock all-sky measurements, a chain of such spectrographs will yield information on the behavior of the neutral atmosphere under varying magnetic conditions. Such a chain called CEDAR Optical Tomographic Imaging Facility (COTIF) was established earlier for the investigations of various nighttime phenomena. Such a chain can now be established with daytime spectrographs as well to investigate various upper atmospheric phenomena round-the-clock. Information from such experiments could be used in assimilative models to better understand the atmospheric behavior in order to make better predictions of both the quiet time and the magnetic disturbance effects on the atmospheric dynamics.

10.4 Launch of Spectrographs in Space Based Platforms:
In this review we have only discussed the applications of spectrographs from the ground. One could potentially use them from space-based platforms (satellites, rockets and balloons) to unravel the mysteries of Earth’s (and also planetary) atmospheric behavior and dynamics.
11. Summary:
We have briefly discussed some of the salient contributions of high-resolution spectrograph (HIRISE), which is capable of making round-the-clock measurements, in advancing our understanding of the daytime upper atmosphere. This brief review gives a flavor of the wealth of information spectrographic measurements have yielded from different latitudes, which have contributed to advancement in our knowledge of the behavior of the daytime upper atmosphere. They include resolving the controversies surrounding the Ring effect behavior, ground-based experimental evidence in OI 630.0 nm dayglow emissions on the redistribution of neutrals in low-latitudes under the effect of a geomagnetic storm, first observations of daytime aurora over Boston, detection of daytime auroral arcs and first observations of magnetic cusps in OI 630.0 nm emissions from Sondrestromfjord. The future of scientific and technical advancements that can be made by these techniques remains bright.

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