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MISE: A multiwavelength imaging spectrograph using echelle grating for daytime optical aeronomy investigations

Duggirala Pallamraju [a,*], Fazlul I. Laskar [a], Ravindra P. Singh [a], Jeffrey Baumgardner [b], Supriya Chakrabarti [c]

[a] *Space and Atmospheric Sciences Division, Physical Research Laboratory, Navrangpura, Ahmedabad, India*
[b] *Center for Space Physics, Boston University, Boston, MA, USA*
[c] *Department of Physics and Applied Physics, University of Massachusetts, One University Avenue, Lowell, MA, USA*

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ABSTRACT

A high-spectral resolution multiwavelength imaging slit spectrograph using echelle grating (MISE) that is capable of measuring daytime optical emissions at multiple wavelengths simultaneously over a large (140°) field-of-view is presented. Optical emissions during daytime (either dayglow or daytime aurora) are buried in the strong daytime solar scattered background continuum and therefore very high spectral resolution measurements are required to obtain their contributions. MISE measures the emission intensities of OI 557.7 nm, OI 630.0 nm, and OI 777.4 nm that originate in the upper atmosphere. The dispersion achieved by the spectrograph at these three spectral regions, respectively, is 0.004, 0.0049, and 0.0059 nm pixel^{-1}. By using an echelle grating as the dispersing element, multiple spectral regions of aeronomic interest are made to fall in the same diffraction angle range so that rotation of grating is avoided. This instrument is immune to ambient temperature fluctuations and vibrations and is suitable for long and continuous field operations. The spectral and intensity calibration of this instrument along with the data analysis methodology are discussed. Sample data of emission intensities from all the three wavelengths mentioned above for a couple of days obtained from Hyderabad (17°N, 80°E; 8.7°N Mag. Lat.) are presented which show a good similarity when compared with those of empirical and photochemical model results. The OI 557.7 nm daytime emissions are measured sparsely from ground-based techniques and ground-based OI 777.4 nm daytime emissions from ground are presented for the first time, to the best of our knowledge. The variability is highlighted and the potential of such measurements to derive information on vertical coupling of atmospheric regions and wave dynamics during daytime are discussed.

1. Introduction

The earth's upper atmosphere consists of both plasma and neutral species. These interact with one another under the influence of magnetic and electric fields, temperature and pressure gradient forces, etc., which results in a host of phenomena that are highly inter-coupled with one another. The plasma dynamics can be investigated by employing radio techniques, such as the radars and digisondes. Investigations of dynamical variations in the neutral species can be carried out by monitoring the temporal variation of atmospheric optical emissions that exist at various altitudes. Atmospheric emissions or airglow are due to chemilumenisence or to photochemical reactions that take place in the upper atmosphere (Chamberlain, 1961). Airglow emissions at different wavelengths emanate from different altitudes depending on the concentrations of atomic or molecular species and the production mechanisms that are responsible for such emissions, and therefore, simultaneous measurement of emissions at multiple wavelengths can be used to infer information on the vertical coupling of atmospheres at high temporal resolutions. Measurement of the variability of emissions over a large field-of-view and for a long duration provides information on the neutral dynamics that exist at the altitude of origin of an emission over a large spatial extent at that altitude. Depending on the time of the occurrence of airglow, namely nighttime, twilighttime, or daytime, it is characterized as nightglow, twilightglow, or dayglow, respectively. Conventionally, ground-based measurements of airglow emissions have been carried out during nighttime—when the solar zenith angle (SZA) is greater than 110°. Information on several issues, such as vertical coupling of atmospheres (e.g., Taylor et al., 1987; Makela et al., 2001; Rajesh et al., 2007), plasma neutral coupling (e.g., Sridharan et al., 1993; Hecht, 2004; Kosch et al., 2007;

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[*] Corresponding author. Tel.: +91 79 26314658.
E-mail addresses: raju@prl.res.in, duggirala_raju@yahoo.com (D. Pallamraju).

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Pedersen et al., 2010; Sekar et al., 2012), traveling atmospheric disturbances (e.g., Otsuka et al., 2004; Martinis et al., 2010; Fukushima et al., 2012), gravity wave propagations (e.g., Sivjee et al., 1987; Shepherd et al., 1995; Lakshmi Narayanan et al., 2010), etc., have been investigated using the nightglow measurements. During twilighttime ($90^{\circ} < \mathrm{SZA} > 110^{\circ}$), when the sunlight is incident at upper atmospheric heights but the observing station is still in the earth's shadow, measurement of emission intensities with time (SZA) have yielded information on the altitude profile of the airglow emissions. During daytime ($\mathrm{SZA} < 90^{\circ}$) the presence of solar photons and extreme ultraviolet radiation enable several avenues of energization of atomic and molecular species which give rise to dayglow emissions, whose magnitude is significantly greater than that of the nightglow intensity at that wavelength. However, the solar scattered background continuum could be orders of magnitudes greater than the dayglow emission intensity. Therefore, innovative methods have to be evolved at to dig out dayglow emissions that are buried in the overwhelmingly strong solar background continuum. Ground-based techniques that have successfully been used to derive dayglow emission intensity are based on photometry (Narayanan et al., 1989; Sridharan et al., 1993a, 1998), spectrometry (Chakrabarti et al., 2001; Pallamraju et al., 2002; Marshall et al., 2011) and interferometry (Barmore, 1977; Cocks et al., 1980; Gerrard and Meriwether, 2011). A review of various attempts made earlier on deriving daytime emissions is described by Chakrabarti (1998). While echelle grating spectrographs have been used for nighttime/twilighttime airglow emission measurements (e.g., Chakrabarti et al., 2001) and for deriving daytime airglow/auroral emission intensities at a single wavelength (Pallamraju et al., 2002), the instrument, MISE, described in this paper is capable of yielding information on dayglow emission intensities at multiple wavelengths at high-spectral resolution simultaneously over a large field-of-view. This is an imaging spectrograph which does not involve any rotation of the grating (to achieve information on multiple wavelengths) or a mirror scanner (to achieve information on different fields-of-view).

2. Description of the multiwavelength instrument

It has been shown in earlier works (e.g., Pallamraju et al., 2002) that a high-spectral resolution measurement of ~ 0.012 nm (at 589.3 nm) is capable of providing information on daytime airglow emission intensities in the visible spectrum. Measurement at multiple wavelengths can be carried out by rotating the grating, but it will be at the cost of temporal resolution, which is not desirable, especially as one of the aims of the optical dayglow measurements is to investigate upper atmospheric wave dynamics, for which high-temporal resolution data are required. The technique being described here is an optical spectrograph which uses an echelle grating. To appreciate the optical design of this spectrograph, let us first consider the grating equation, which is:

$$n\lambda = d(\sin\alpha + \sin\beta) \tag{1}$$

where, n is the order of diffraction, λ is the wavelength, d is the grove spacing on the grating, α and β are the angles of incidence and diffraction.

Differentiating Eq. (1), we get the angular dispersion ($d\beta/d\lambda$) as:

$$d\beta/d\lambda = n/(d\cos\beta) \tag{2}$$

Substituting for n/d from Eq. (1) in Eq. (2) we get:

$$d\beta/d\lambda = (\sin\alpha + \sin\beta)/(\lambda\cos\beta) \tag{3}$$

Therefore, it can be seen from Eq. (3) that for a given wavelength, the angular dispersion can be considered to be solely a function of the angles of incidence and diffraction. It is high for high angles of incidence and diffraction, α and β. Gratings that are designed to operate at high incidence and diffraction angles are called echelle gratings. The blaze angle for such a grating is required to be close to angles α and β to obtain a high grating efficiency. At high blaze angles, the facet length of the grating is required to be large, as it varies as $d \times \cos\beta$, and hence, large grove spacing, d, is required. According to Eq. (1), it can be seen that for a given wavelength, greater values of angles α and β and larger groove spacing, d can be supported at high values of n. Thus, echelles typically operate at high orders of diffraction (>40). Although echelle gratings provide high-spectral resolution, at high diffraction orders there would be several wavelengths of different orders that would appear at the same location. This problem of order overlap mainly prevented their use widely in the past. In the recent times, as narrow-bandwidth interference filters which allow light from only the required wavelength range to pass through at a given diffraction angle have become available, the usage of echelle gratings have gained importance (e.g., Chakrabarti et al., 2001, 2012; Pallamraju et al., 2002; Galand et al., 2004; Pallamraju and Chakrabarti, 2006; Marshall et al., 2011).

It is known that measurement of the intensity variations of optical airglow emissions at multiple wavelengths is an effective passive remote sensing method to investigate various aspects of vertical coupling of atmospheres. The three emission lines that have been chosen for upper atmospheric investigation are OI 557.7 nm, OI 630.0 nm, and OI 777.4 nm which originate from around 100 km, 230 km and peak altitude of the ionosphere (anywhere between 250 and 400 km), respectively, during daytime. OI 557.7 nm dayglow emission has a second peak at a higher altitude ~ 180 km (Zhang and Shepherd, 2004). Simulations have been performed by using the grating equation and for f/11 input optics to obtain the right combination of ruling density and blaze angle of a grating such that all the three wavelengths simultaneously fall on approximately a 24 mm × 24 mm area at the image plane where filters are placed. Care was taken to consider specifications of commercially available echelle gratings so that custom made optical components are avoided

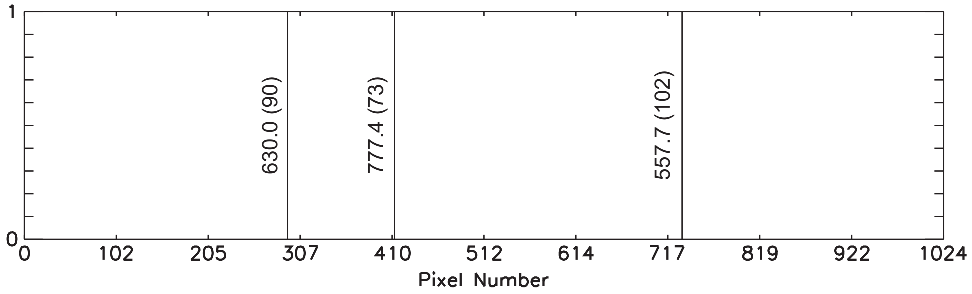

Fig. 1. Ray trace simulation result showing the relative positions of different wavelengths that would appear on a detector. This was carried out to determine the specifications of the grating that would be required (ruling density, blaze angle, etc.) to achieve the objective of making simultaneous measurements at OI 557.7 nm, OI 630.0 nm, and OI 777.4 nm emissions.