COINCIDENT IMAGING AND SPECTROMETRIC OBSERVATIONS OF ZENITH OH NIGHTGLOW STRUCTURE

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Abstract. During the ALOHA-90 campaign a novel comparative study was made between near infrared wave structure imaged in the zenith using a CCD camera and that detected at infrared wavelengths by a Fourier Transform Spectrometer. Coincident measurements were made briefly on several occasions and for an extended period on 31 March. The temporal variations imaged in the near infrared structure during this night almost completely matched those detected in the OH (3,1) band spectrometer data when similar viewing fields were compared. However, the image data also displayed small scale wave forms that were not resolved by the larger field instrument. These structures exhibited significant changes in brightness and position on a time scale much shorter than the local Brunt-Väisälä period indicating that very high resolution measurements are necessary to investigate short period (<20 min) upper atmospheric wave motions.

Introduction

For many years spectrometric measurements of the night sky have been made to ascertain the nature and origin of the upper atmospheric nightglow emissions. More recent investigations have been into quasi-periodic variations which often exhibit characteristics of freely propagating internal gravity waves [Noxon, 1978; Viereck and Deehr, 1989; Swenson et al., 1990]. Observations of the bright infrared OH Meinel band emissions, which originate from a well defined layer centred at ~87 km, have proved most useful in these studies. As the lower rotational levels of the OH emission are usually in thermodynamic equilibrium with the local atmosphere, measurements of both the emission intensity and its rotational temperature can be used as a tracer of the wave motion. Furthermore, long exposure photographic and low light video images of the near infrared (NIR) OH emission can be used to investigate the 2-dimensional horizontal properties of the wave disturbance [Moreels and Herse, 1977; Armstrong, 1986; Taylor et al., 1987].

In general, spectral observations suffer from difficulties in distinguishing between the induced temporal and spatial variations. Recently Taylor et al. [1991] have reported the results of a simultaneous imaging and interferometric study

of short period (~14 min) wave structure in the OH nightglow emission. The measurements were made at low elevations, ~15°, (to aid the video observations), and show in detail the relationship between a coherent gravity wave pattern and the induced intensity and temperature perturbations. During ALOHA-90 a similar comparison was made. Here we report novel observations of a small scale wave pattern imaged in the zenith and compare the intensity records with those detected by the spectrometer.

Observations

The instruments used were a CCD camera (University of Southampton) and a Fourier transform spectrometer (The University of Western Ontario), both of which were located on Haleakala Crater, Maui (20.8°N, 156.2°W, 2970m). A short description of the instruments and their operational characteristics is given by Gardner [1991]. The CCD camera imaged structure in the submicron nightglow emissions (half bandwidth 780~1000 nm) while the spectrometer measured the zenith intensity of several OH Meinel bands in the wavelength range 1000-1650 nm.

Most of the time the camera was used to investigate the low elevation sky in the direction of the aircraft flight path [Gardner, 1991]. However, on several occasions a search for structure in the zenith sky was made. Table 1 lists the dates and times of these measurements. Structure was imaged on every occasion that zenith measurements were attempted (total of six nights) but the observations were usually brief enough to determine only the scale size and orientation of the wave forms. However, on 31 March a series of images were recorded for detailed comparison with the spectrometer measurements.

TABLE 1. Dates and times when NIR structure was imaged in the zenith by the CCD camera.

DAY	DATE	TIME (UT)
081	22/3	15:30
082	23/3	14:53
087	28/3	15:16
089	30/3	12:22 - 12:59
090	31/3	09:50 - 10:00
		13:00 - 14:51
092	02/4	12:19 - 12:56

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31 March Display

A summary of the nightglow display imaged at low elevations during this night is given by Taylor and Edwards, [1991]. To the west and north of the site a uniform wave pattern of horizontal wavelength ~20 km was detected over a period of several hours (see their Figure 3). Images of wave structure in the zenith were obtained around 10:00 UT and again over three hours later. Figure 1 is a collection of six CCD images showing examples of the zenith nightglow structure recorded at 4 minute intervals from 13:14 UT. The pictures are quite exceptional and show considerable evolution and movement of the structures. Each image has been flat fielded (to remove the effects of lens vignetting etc that are present in the original records), and color enhanced to highlight the spatial features of the structures which exhibited low contrast ($\leq 5\%$). After 13:18 UT several wave-like forms are evident; the east-west orientation and separation of these structures is similar to those observed in the low elevation pattern, confirming its large

geographic extent ($>250,000\text{ km}^2$). A total of 32 images of the zenith sky were recorded over the period 13:00-14:51 UT. The field of view of the camera (55° by 30°) was larger than the spectrometer sample area (30° circular), but smaller than the Aerospace Corporation camera (60° by 40°). The variation in responsivity of the spectrometer over its viewing field has not been measured.

Results and Discussion

Images showing nightglow wave structure at high elevations and in the zenith are rare [Peterson and Adams, 1983]. To date most of the video and photographic measurements reported in the literature have been made at low elevation angles to benefit from the 2-3 fold increase in emission intensity which occurs due to line of sight integration through the nightglow layer. The observations reported here were made using a new broad band nightglow imager and clearly demonstrate the existence of NIR structure in the zenith as well as at low elevations. Although similarities in the separation and

Fig.1. Series of CCD images showing small scale wave structure in the near infrared zenith nightglow emissions. Each image has been flat fielded and color enhanced to highlight the wave features. The structures appear mainly yellow-green but brighter features are red. The camera was aimed at an azimuth of 280° and the near east-west aligned waves are almost vertical in the images.

orientation of the wave forms are evident in each image, the intensity distribution is different, indicating considerable evolution of the wave field in a relatively small time interval (≤ 4 min).

By summing the video signal in a 30° square centred on the optic axis, the intensity of the NIR TV data can be compared with the OH (3,1) band intensity measured by the spectrometer. Figure 2a plots the relative intensity derived from the spectrometer data (averaged over 1 min intervals) during the period 13:00–15:00 UT [Turnbull and Lowe, 1991]. During the night both the OH relative intensity and the rotational temperature exhibited considerable wave-like variations. In particular a large scale perturbation of quasi-period ~ 2.2 hours was detected. This wave motion is present in the data from the larger field of view Aerospace camera [Hecht and Walterscheid, 1991]. However, the spectrometer also registered much smaller scale structures which are not seen in the Aerospace data, possibly due to averaging effects. These variations are significant and should be present in the image data.

Figure 2b plots the relative intensity derived from the 32 CCD images. The data were recorded at intervals ranging from 1 to 4 minutes using a fixed exposure time of 30s. Each point represents the average intensity of the video signal over a 30° square field. (Note, the dashed line linking the points serves only as a guide to the eye.) It is immediately apparent that the small scale intensity variations in the spectrometer data are also in the CCD data and with no obvious time shift. The video data were the sum of several signal components existing within the broad pass band of the camera (half-width 780–1000 nm) and include the OH (5,1), (6,2), (7,3), (8,4), (3,0) and (9,5) Meinel bands, the $O_2(0,1)$ Atmospheric band near 865 nm, the nightglow continuum and integrated starlight. However, as the temporal variations in the OH (3,1) band intensity are almost exactly duplicated in the image data this indicates that the variations in structure in the images were primarily due to changes in the OH emission. This is to be expected as the OH emission dominates this region of the nightglow spectrum having an integrated emission intensity of typically 12kR.

Alternatively, the intensity variations detected by both instruments could have been due to thin meteorological cloud (although none was visible). However, as the induced intensity and rotational temperature perturbations were highly correlated [Turnbull and Lowe, 1991], with no significant scatter that would result from thin cloud, there can be little doubt that the structures were caused by changes in the OH emission. Any similar perturbations in the NIR continuum and/or the $O_2(0,1)$ band emissions were therefore comparatively faint and/or were in near phase with the OH signal. The primary effect of these emissions was to reduce the contrast of the OH structures.

The wave pattern imaged by the TV camera shows several features of smaller dimensions than the spectrometer sample area. (An indication of the limits of the circular spectrometer field is shown in Figure 1 by the large white box which shows the 30° square video sample area.) Thus, on this occasion the spectral signal was the spatial average of more than one nightglow feature. (Note the spectrometer data will be of higher spatial resolution

Fig.2. Relative intensity of (a) the OH (3,1) band recorded by the spectrometer using a 30° circular field of view and, (b) the broad band NIR structure derived from the CCD images using a 30° square sample area.

than indicated by this box due to the somewhat smaller area of the 30° circular field.) To investigate the temporal properties of the display in more detail the CCD data have been re-analyzed using a smaller sample area of 5° square (marked by the small white box) which corresponds to a zenith "footprint" of ~ 8 km square. As the wavelength of the OH pattern was ~ 20 km individual bright and dark structures of this dimension should be resolved.

Figure 3 shows the relative intensity data for this sample field. For comparison the data have been plotted using the same intensity and time scales as Figure 2b. Although similar features are present in both plots the short wavelength structures are now evident and the overall contrast of the variations is increased. More critically, although a 4 minute sample interval (13:00–14:00 UT) is ample for tracking the large scale perturbations present in the figure, it is too long for registering accurately the small scale variations. After 14:15 UT the sample interval was reduced to 1 min and the variations are clearly detected. At the time of recording the data little or no change in the images were observed by eye. However, Figure 3 shows that significant changes in the integrated nightglow brightness took place on a minute-by-minute time scale.

Studies of wave structure in the upper atmosphere usually assume the local Brunt-Väisälä (buoyancy) period, τ_b , as a natural lower limit for the temporal resolution of the measurements. At nightglow altitudes τ_b is typically 5–6 min. Wave motions with phase velocities of a few tens ms^{-1} can propagate significant distances (several km)

Fig.3. Relative intensity of the CCD data determined using a 5° square sample area. For comparison the data are plotted on the same scales as Figure 2.

during this time. These measurements demonstrate the need for high temporal and spatial resolution when investigating the properties of short period (<20 min) waves that frequently occur in the nightglow emissions.

Summary

The good seeing conditions at this site permitted OH nightglow wave structure to be imaged in the zenith. The close similarity in the relative intensity data measured by the spectrometer and the CCD camera indicates no observable difference in the wave structure arising primarily from high OH vibrational levels ($v' > 5$) compared with that observed in the $v' = 3$ level of the OH (3,1) band. To date most image data on the nightglow emissions have been obtained at low elevations, and comparative studies with other optical devices are rare [Taylor et al., 1991]. The extension of high resolution imaging measurements into the zenith has several advantages but is made at the expense of signal level.

During ALOHA-90 NIR wave patterns of horizontal wavelength $\ll 100$ km were observed on several occasions. Large field instruments will naturally integrate out much of this structure which appears to be relatively common over both mountain and oceanic sites. Coincident imaging and spectrometric measurements of the OH emission are highly complementary: the spectrometer establishes the spectral integrity of the emission and gives accurate intensity and temperature data while the imager records the 2-dimensional spatial structure of the wave perturbation, its motion and temporal evolution.

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