1. Introduction

Measurements of atmospheric emissions, such as aurora and airglow, using Fabry-Perot interferometers (FPIs) have enabled the remote sensing of atmospheric wind and temperature from the ground and in space (e.g., Rees et al., 1984; Killeen and Roble, 1988; Hernandez and Roble, 1995; Naka-jima et al., 1995; Aruliah et al., 1996; Dyson et al., 1997; Plagmann et al., 1998; Biondi et al., 1999). Some of these FPIs can measure different airglow/auroral lines by changing the interference filter as a pre-disperser. However, such a system does not allow the simultaneous measurement of different lines. Ishii et al. (1997) developed an imaging FPI with two sets of filters and imaging detectors below the etalon to measure OI (558 and 630 nm) auroral/airglow lines simultaneously. Biondi et al. (1995) and Shiokawa et al. (2001) have used a new device, highly sensitive liquid-nitrogen cooled-CCD detectors, as an imaging detector for their FPI. These authors, however, have pointed out that the use of liquid nitrogen for CCD cooling causes unexpected movement of the CCD detector of 0.1–0.2 pixels, which directly affects the wind velocity determination in the high-resolution interferometry of the FPI. Moreover, unmanned (automated) operation of the FPI measurement is difficult for the liquid nitrogen cooling system.

In this paper, we report performance of a two-channel FPI, which has two sets of filters and cooled-CCD detectors below the etalon with thermoelectric cooling system (without liquid nitrogen), in order to measure OI (558 and 630 nm) airglow lines simultaneously. Automatic operation of the FPI using the thermoelectric cooling system was started beginning in October 2000. The wind velocities measured by the FPI fit well with those obtained from radar for both airglow lines.

2. Instrumentation

Figure 1 shows a schematic of the FPI used in the present study. It has telecentric front optics to make a parallel light beam (maximum angle = 0.7°) through the etalon (ET, d=15 mm, φ=116 mm), and two CCD detectors (512 × 512 pixels) with interference filters to measure the airglow emissions at 558 and 630 nm separately. The front optics A has a zoom lens with a field-of-view of 9.5° as an objective and a mirror at the top for azimuthal scanning.

The original system of the present FPI had one fish-eye imaging lens as the front optics and three CCD detectors with a liquid-nitrogen cooling system (Shiokawa et al., 2001). Because the imaging FPI showed significant ambiguity in its measurements of the absolute value of wind velocity, we modified the imaging FPI into an azimuthal-scanning FPI by replacing the front telecentric optics from those with a fish-eye lens to those with a zoom lens and a scanning mirror. The CCD detectors with a liquid-nitrogen cooling system were also replaced by those with a thermoelectric cooling system, because the liquid-nitrogen cooling system causes unexpected displacement of the CCD detectors, as described by Shiokawa et al. (2001). One of the CCD detectors used to measure 839.9-nm airglow (OH) was removed from the present system.

The FPI measures the Doppler shift of the airglow emissions at a zenith angle of 50° ± 4.75° and in the four azimuthal directions of N, S, E, and W. Assuming that the horizontal wind is uniform in the field-of-view of the FPI and that the vertical wind velocity is negligible compared to the horizontal wind velocity, the FPI measures line-of-sight components of horizontal wind vectors by taking a difference in the interference fringe locations in opposite directions (N-
A: zoom lens (NIKON 135mm/F8.0, FOV=9.5 (deg))
with a telecentric lens cell near the focal plane
and a 25 (deg) mirror above for scanning
B: achromat, f=800mm, Φ=50mm
C: achromat, f=988mm, Φ=118.5mm
D: achromat, f=470mm, Φ=120mm
E, F: achromats for band-pass filter
SH: shutter
IS: integrating sphere
DF1: diffuser (manual insert)
DF2: diffuser
LS: laser beam
PR: prism
SP: AR coated 45(deg) glass window
ET: Fabry-Perot etalon (Φ=116mm, d=15mm)
R=0.85 ±0.03 (550-850nm)
Finesse: 19.3
free spectral range: 1.3×10^5 nm at 630nm
TH: insulated heating box
M: 45 (deg) mirror
DM1,2: dichroic mirror
FT1, FT2: band-pass filters on filter wheels

Fig. 1. Schematic diagram of the two-channel Fabry-Perot interferometer.

S and E-W). These assumptions usually hold in the midlatitudes, while they are not applicable for high-latitude auroral zone (Smith, 1998).

Continuous measurement with the FPI has been carried out since October 2000 at Shigaraki (34.8°N, 136.1°E), Japan, with an exposure time of 13.5 min for each direction. The time resolution used to obtain a set of zonal and meridional wind velocities is one hour. This time resolution is obtained by 2×2 binning of the CCD pixels, which makes the output count four times larger than that without the binning. Since October 2001, a higher time resolution of 15 min (3.5-min exposure for each direction) has been achieved using 4×4 binning of the CCD pixels.

Figures 2(a) and (b) show examples of airglow fringes obtained at Shigaraki with the FPI for 630- and 558-nm airglow, respectively, at 1948:00–2001:30 LT (13.5-min exposure) on March 26, 2001. The left panels show fringe images in the southward direction. Because of the interference by the etalon in the optics, the line emission from the airglow produces concentric circles (fringes) on the CCD detectors. The right panels show fringes obtained by integrating the images in the left panels for all azimuthal angles of the fringe circles. The relatively high background counts (∼800 in Fig. 2(a) and ∼600 in Fig. 2(b)) are not because of the background continuum emission from the sky, but mainly because of the read-out offset of the CCD. We will discuss the effect of this CCD read-out noise in Section 4.

By fitting a Gaussian function to the fringes in the right panels, we determine the peak locations of the first and second fringes in units of radius squared, which can be directly converted to wind velocities. For example, northward wind velocity \( v_N \) can be obtained by the following equation:

\[
v_N = \frac{c \cos \theta}{4 f^2 - (r_S^2 + r_N^2)} \left( \frac{r_S^2 - r_N^2}{1 - r_N^2} \right)
\]

where \( r_N \) and \( r_S \) are the peak location (radius) of the northward and southward fringes, respectively, \( f = 470 \text{ mm} \) is the focal length of the collimator lens (D in Fig. 1), \( c \) is the speed of light, and \( \theta \) is the angle of the line-of-sight from the horizontal plane. Equation (1) is derived from the interference condition

\[
m = \frac{2 \mu \lambda_0 (1 + v_N \cos \theta / c)}{\lambda_0 (1 + v_N \cos \theta / c)} (1 - r_N^2 / 2 f^2)
\]

\[
= \frac{2 \mu d}{\lambda_0} (1 - v_N \cos \theta / c) (1 - r_S^2 / 2 f^2)
\]

where \( m \) is the integer number of the interference, \( \mu \) is the refractive index, and \( \lambda_0 \) is the wavelength of the airglow without the Doppler shift. Because \( 4 f^2 - (r_N^2 + r_S^2) \geq 4 f^2 \) in
Eq. (1), the FPI measures the northward wind velocity from the difference between the northward and southward fringe peak locations.

It is interesting to note that for the zero vertical wind velocity, the etalon spacing \( d \) can be measured by using the value of \( r_N^2 + r_S^2 \), i.e.,

\[
d = \frac{m\lambda_0}{\mu} \frac{2f^2}{4f^2 - (r_N^2 + r_S^2)}
\]

By calculating \( r_N^2 + r_S^2 \), we can monitor the etalon spacing drift in the FPI.

3. Observation

Figures 3(a)–(g) show the directional wind (relative variation of \( r^2 \) in units of wind velocity), etalon gap drift estimated from \( r_N^2 + r_W^2 \) and \( r_N^2 + r_S^2 \) in units of wind velocity, fitting error, peak counts, and eastward and northward wind velocities, respectively, obtained for 558-nm airglow at Shigaraki on March 26, 2001. The interference condition (2) was used to convert the unit from radius squared to m/s. Figures 4(a)–(g) show the same parameters measured for 630-nm airglow on the same night. Both the mesospheric (Figs. 3(f) and 3(g)) and thermospheric (Figs 4(f) and 4(g)) wind velocities show nocturnal variations. The variations in Fig. 4(f) and 4(g) represent the typical tidal variations in the nighttime midlatitude thermosphere, i.e., a southward wind around midnight and a changing trend from eastward before midnight to westward after midnight (e.g., Biondi et al., 1999; Kawamura et al., 2000).

To check the reliability of the wind velocities measured with the FPI, we simultaneously observed wind velocities with the FPI and the MU radar in both the mesosphere and the thermosphere at Shigaraki on March 26, 2001, during the MTEC-E (Mesosphere-Thermosphere Experiments for Coupling Studies at Equinoxes) campaign. The MU radar simultaneously measured the mesospheric wind velocities from meteor echoes (Nakamura et al., 1991) and the thermospheric wind velocities from ion drift measurement (Oliver et al., 1998) with a time resolution of 1.5–2 hours.

The wind velocities measured by the MU radar from meteor echoes are plotted in Figs. 3(f) and 3(g) as dashed curves for altitudes of 90, 92, and 94 km (around the typical altitude of the 558-nm airglow layer). The radar wind velocities at 92 km are closest to the FPI wind velocities in both the northward and eastward directions, with a maximum difference of \( \sim 20 \text{ m/s} \).

The thermospheric wind velocities estimated by the MU radar from the ion drift measurement are plotted in Fig. 4(g). The MU radar can measure ion drift velocity in the ionospheric F-layer along the local magnetic field line. The ion drift velocity is the vector summation of the meridional neutral wind velocity through ion-neutral collision and the field-aligned ion diffusion velocity. By taking the diffusion velocity from the MSIS-86 model atmosphere, we can convert the measured ion drift velocity into the meridional neutral wind velocity. Thus, the MU radar wind in the thermosphere is not a direct measurement of the neutral motion. On the other hand, the FPI gives the neutral wind velocity directly from the Doppler shift of the 630-nm airglow emission. The comparison in Fig. 4(g) shows a good correspondence between the meridional wind velocities measured by these two techniques, with a maximum difference of \( \sim 40 \text{ m/s} \).

4. Discussion

For the wind measurement by FPI, the random error of Gaussian fitting can be estimated from the count rate of the
fringe data. Figure 2 shows the average counts for each pixel in the fringe images. The peak counts are \(300\) for both 558 nm and 630 nm. The variations of peak counts on this night are shown in Figs. 3(e) and 4(e). For 558 nm, the counts are \(400\). For 630 nm, they decrease from \(400\) to \(100\) due to the decrease of electron density at night. These counts give root-mean-square (r.m.s.) noise \(\sigma_n\) of 20 counts and 20–10 counts for 558 nm and 630 nm, respectively. The read-out noise and dark counts of the CCD give typical r.m.s. noise \(\sigma_{\text{CCD}}\) of \(\sim10\), which is comparable to the r.m.s. noise \(\sigma_n\) of airglow counts. The signal-to-noise ratio \(S/N\) is given by (signal counts) / (\(\sigma_n + \sigma_{\text{CCD}}\)), which is \(\sim10\) and \(\sim10–3.3\) for 558 nm and 630 nm, respectively.

These values of \(\sigma_n\), \(\sigma_{\text{CCD}}\), and \(S/N\) are for each CCD pixel. The actual \(S/N\) for the fitting is much larger because of the azimuthal integration of the fringes. Typically, 350–400 pixels and 650–700 pixels are integrated for the first and second fringes, respectively. Thus, the actual \(S/N\) for the Gaussian fitting are \(\sqrt{350–700}\) times larger than the \(S/N\) per each pixel. The random errors of Gaussian fitting estimated from these considerations are shown as error bars.
of wind velocities in Figs. 3(f), 3(g), 4(f), and 4(g). The estimated random errors are ~5–8 m/s for 558 nm and ~10–50 m/s for 630 nm.

It should be noted that the Gaussian fitting to the first and second fringes are made independently. The difference of the wind velocities obtained from the first (crosses) and second (circles) fringes are mostly less than the random errors shown by the error bars.

As indicated by Eq. (3), the etalon spacing drift can be estimated for the present FPI. Figures 3(b), 3(c), 4(b), and 4(c) show a drift in the etalon spacing, particularly for the interval before midnight. This is probably because of the temperature change of the etalon from daytime to nighttime, which was not fully cancelled out by an air conditioner in the FPI hut. After midnight, this spacing drift becomes negligible.

Because of this spacing drift, the radius $r$ of the fringes uniformly decreases toward midnight. This effect is seen in Figs. 3(a) and 4(a), which indicate the change of the fringe radii in units of wind velocity. Because the FPI measures the wind velocities obtained from the second fringes are made independently. The difference of the wind velocities in Figs. 3(f), 3(g), 4(f), and 4(g). The estimated random errors are ~5–8 m/s for 558 nm and ~10–50 m/s for 630 nm.

5. Conclusion

We have developed a two-channel FPI with two cooled-CCD detectors to measure mesospheric and thermospheric wind velocities simultaneously at midlatitudes through the 558- and 630-nm airglow emissions. The FPI was originally developed as an imaging FPI with a fish-eye lens as the front optics and cooled-CCD detectors with liquid-nitrogen cooling system. However, the front imaging optics were replaced by the scanning optics to avoid the inherent ambiguity of the imaging FPI in determining absolute wind velocities. The liquid-nitrogen cooling system was replaced by thermoelectric cooling system to avoid unexpected displacement of the CCD detectors. The employment of the thermoelectric cooling system also enables us automatic operation of the FPI. The random errors of the wind measurement are estimated to be ~5–8 m/s and ~10–50 m/s for 558 nm and 630 nm, respectively, for the data of March 26, 2001.

Comparison with the MU radar winds of both the mesosphere and the thermosphere for the data of March 26, 2001, gives reasonable agreement, with a maximum difference of ~20 m/s (mesospheric winds for 558-nm airglow) and ~40 m/s (thermospheric winds for 630-nm airglow). The FPI has routinely measured mesospheric and thermospheric wind at Shigaraki since October 2000. Summary plots from these routine observations (similar to Figs. 3 and 4) are available at http://stdb2.stelab.nagoya-u.ac.jp/omti/.

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