https://doi.org/10.5194/egusphere-2026-2475
Preprint. Discussion started: 21 August 2026

A Compact Fabry-Perot Interferometer with a Solid Etalon for Measuring Upper Atmospheric Wind and Temperature

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Abstract. A compact solid etalon Fabry-Perot interferometer (SEFPI) with an effective aperture diameter of 70 mm has been developed for ground-based measurements of upper atmospheric winds and temperatures at an altitude of approximately 250 km. Unlike conventional FPIs employing air-spaced etalons, the SEFPI uses a solid etalon, enabling a more compact, lightweight, and cost-effective instrument design, while requiring stringent thermal stabilization. Laboratory validation using an acousto-optic frequency shifter (AOFS) to generate controlled Doppler shifts demonstrated the SEFPI's high measurement accuracy, with an average wind uncertainty of 0.42 m/s and a root mean square error (RMSE) of 0.61 m/s. Field comparison validation was conducted via coincident ground-based measurements with two interferometry techniques. The first employed a Dual-Channel Optical Interferometer (DCOI), while the second utilized a well-established FPI employing a 100 mm diameter air-spaced etalon. The SEFPI measurements exhibited strong agreement with both instruments, yielding Pearson correlation coefficients exceeding 0.84. Statistical analysis yielded an overall mean wind difference of 1.88 m/s relative to the co-located DCOI instrument and 5.58 m/s relative to the conventional FPI located 502 km away. Temperature comparisons between the two FPIs revealed a correlation coefficient of 0.86 and an average difference of 62.38 K.

1 Introduction

The Earth's upper atmosphere serves as a key transition region from the lower atmosphere to outer space and is highly dynamic. This region is dominated by a combination of in-situ forcing, driven by the absorption of solar extreme ultraviolet (EUV) radiation, and upward-propagating atmospheric disturbances such as tides, gravity waves, and planetary waves from the lower atmosphere (Fisher et al., 2002). Neutral winds and temperatures play a critical role in determining the state, evolution, and dynamics of the global ionosphere-thermosphere system. Furthermore, dynamical changes in neutral winds directly or indirectly perturb the ionosphere and hence can give rise to electric fields and plasma instabilities. These phenomena, in turn, affect the global redistribution of energy and momentum deposited at high latitudes by the magnetosphere (Dhadly et al., 2023; Makela et al., 2014, 2021). Despite their recognized significance, neutral winds and temperatures remain among the least comprehensively sampled state parameters within the global upper atmosphere even after decades of observations. Accurate measurements of upper atmospheric winds and temperatures are therefore essential for advancing our understanding of these coupled processes. This endeavor advances our understanding of the complexities of the Earth's atmosphere, as well as our ability to predict the effects of solar and geomagnetic activity, atmospheric perturbations, and other phenomena on the Earth's environment and technological systems (Immel et al., 2021; Li et al., 2023; Liu et al., 2015; Oyama et al., 2024; Yang et al., 2020).

One of the most effective methods for measuring neutral winds and temperatures, particularly in the upper atmosphere, is through airglow observations using interferometric spectroscopy. Airglow, an important tracer of variability in the middle and upper atmosphere, is produced by atmospheric photochemical processes (Gao et al., 2011; Saha and Pallamraju, 2022). Photons

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emitted during these processes enable passive optical remote sensing of winds and temperatures. Among passive optical techniques, the Fabry-Perot interferometer (FPI) has remained one of the most widely used instruments for nocturnal measurements of neutral winds and temperatures (Dhadly et al., 2023; Englert et al., 2010; Grawe et al., 2019; Meriwether, 2006; Okoh et al., 2022; Wu et al., 2019). It operates by monitoring Doppler shifts and spectral broadening in selected nightglow emissions. While radars, lidars, and ionosondes provide valuable data on atmospheric parameters at various altitudes, passive optical interferometry remains one of the few ground-based techniques capable of directly measuring atmospheric winds at altitudes around 250 km (Dao et al., 1995; Englert et al., 2012; Jia et al., 2025; Kristoffersen et al., 2024; Li et al., 2025; Sun et al., 2024; Tsuda, 2014; Yi et al., 2019; Yue et al., 2022; Zhang et al., 2025).

Over the past few decades, various types of FPIs have been developed to meet the increasing demand for accurate wind and temperature measurements relevant to space environment monitoring. Based on their optical configuration and field of view (FoV), FPIs can generally be categorized as all-sky and single-point measurement systems. All-sky FPIs use a fore-optics assembly that includes a fisheye lens to achieve a wide FoV, enabling simultaneous measurements of wind and temperature over a large region of the sky, providing high temporal and spatial resolution (Anderson et al., 2009; Aruliah et al., 2010; Biondi et al., 1995; Conde and Smith, 1997; Shiokawa et al., 2001). In contrast, single-point FPIs with a narrow FoV possess simpler optical configurations. For wind and temperature measurements, single-point FPIs require a sky scanner equipped with a dual-axis mirror to steer the system, directing light from any region of the sky into the system aperture (Makela et al., 2009a; Meriwether et al., 1983; Shiokawa et al., 2012; Trondsen et al., 2019; Vasilyev et al., 2017; Wu et al., 2004). A complete measurement cycle usually includes observations at the zenith and the four cardinal directions (east, south, west and north) at 45° elevation, and is typically followed by laser calibration. To date, virtually all existing FPI systems employ air-spaced etalons enclosed in metal housings to ensure thermal and mechanical stability (Hernandez, 1980; Meriwether, 2006; Nakajima et al., 1995; Vasilyev et al., 2017; Wang et al., 2025; Wu et al., 2004). To increase the signal-to-noise ratio (SNR) for observing faint nightglow, FPIs generally utilize large-aperture etalons, often with diameters of at least 100 mm (Anderson et al., 2009; Jacka et al., 1980; Schmidt et al., 2025; Sivjee et al., 1980; Wang et al., 2016). However, such etalons are typically heavy and expensive, as fabrication complexity increases exponentially with aperture size. As a result, the establishment of large-scale ground-based FPI observational networks has been hindered by the bulky and expensive nature of these instruments.

To address these limitations and advance ground-based passive optical observational networks for the middle and upper atmospheric measurements, a novel solid etalon Fabry-Perot interferometer (SEFPI) has been developed and validated through both laboratory experiments and field observations. For applications where instrument size and weight are constrained, the SEFPI system built from a solid etalon is an interesting option to explore, as it is compact, pressure-insensitive and low-cost, and provides an alternative to customized air-spaced etalons. The paper is organized as follows: Section 2 details the optical design of the SEFPI. In Section 3, the instrument function of the FPI is adapted for the solid etalon, and a forward model for retrieving wind and temperature is derived. Section 4 demonstrates SEFPI's robust wind measurement capabilities using newly developed high-accuracy laboratory setups for simulating wind speed. Section 5 presents SEFPI's initial wind and temperature measurements at 250 km altitude and validates them by cross-comparing them with data from two independent ground-based passive optical instruments deployed at two sites. Finally, Section 6 summarizes and discusses the findings of this study.

2 Instrumentation

The SEFPI's optical configuration and a photograph of the instrument deployed at the observation station are shown in Figure 1, with detailed descriptions and specifications of each component provided in Table 1. A key component of the system is the sky scanner, which is equipped with a pair of dual-axis steering mirrors. These mirrors can be independently rotated to select the desired azimuth and zenith angles, directing light from any region of the sky into the SEFPI aperture. The sky scanner is

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mechanically isolated from the main SEFPI body and mounted separately above it to minimize mechanical vibrations and associated optical distortions during scanning (Nakamura et al., 2017).

An optical coupling box, housing a spectral wedge and a high-reflectivity mirror, is positioned beneath the sky scanner. The spectral wedge has a reflectivity of 0.95 and a transmittance of 0.05, allowing a frequency-stabilized He-Ne laser beam to be coupled into the system for calibration. A 250-mm-long baffle is installed below the optical coupling box to suppress stray light and limit the FoV to 2.5°.

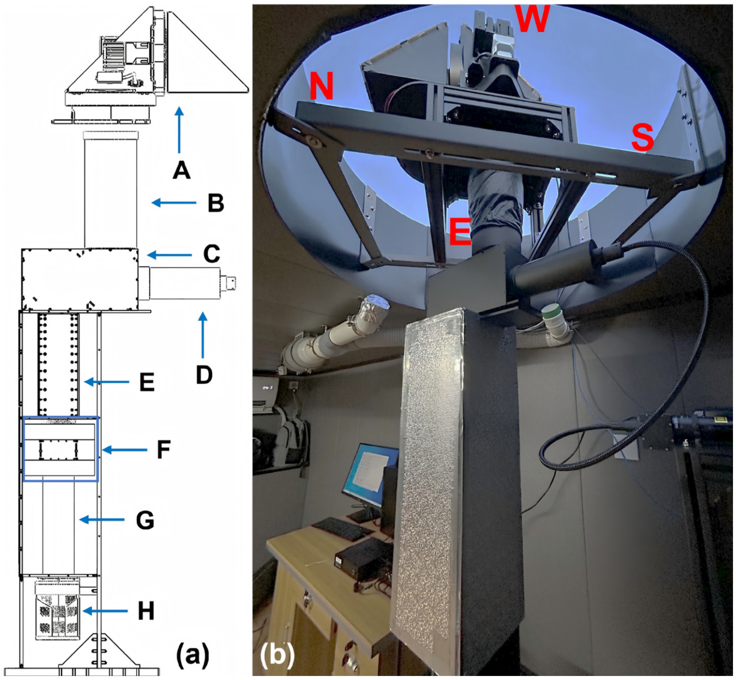

Figure 1. (a) Optical configuration and (b) photograph of the SEFPI system deployed at the observation station. The labeled components are: (A) sky scanner; (B) incident light tube; (C) optical coupling box for laser calibration and airglow observations; (D) laser scattering tube; (E) baffle; (F) interference chamber housing the bandpass filter and solid etalon; (G) focusing lens assembly; and (H) CCD detector.

The quasi-parallel beam from the baffle enters a sealed, temperature-controlled housing containing a bandpass interference filter and a solid etalon. The interference filter has a diameter of 75 mm, a central wavelength of 630.0 nm, and a bandwidth of 2.0 nm. The filtered atomic oxygen red-line emission then enters the solid etalon, where it produces concentric interference fringes. The solid etalon has a diameter of 70 mm and a thickness of 16 mm. The solid etalon is fabricated from fused silica, with a refractive index of 1.457, a reflectivity of 79%, and a surface flatness better than λ/100 over the clear aperture. Because the refractive index and physical thickness of the solid etalon are more sensitive to temperature variations, the spectral stability achievable for the typical etalon temperature stability of 0.1 °C becomes a major technical challenge (Makela et al., 2009b; Schmidt et al., 2025; Shiokawa et al., 2012; Wang et al., 2016; Wu et al., 2004). To address this issue, the solid etalon is housed in a temperature-controlled chamber maintained at 30 °C using an independently developed proportional-integral-derivative (PID) control system, with a target temperature stability of ±0.005 °C. During the 36 effective nighttime field observation periods, the measured etalon temperature showed a mean absolute deviation of 0.0001 °C from the set point, with a standard deviation of 0.0026 °C (see Appendix, Figure A1).

An achromatic lens with a diameter of 100 mm and a focal length of 300 mm is used to image the interference pattern onto the focal plane of a cooled CCD detector. The detector is a PIXIS 1024B CCD camera with a 1024×1024 pixel array and a pixel size of 13 μm. It is cooled to -70 °C to reduce thermal noise during long-exposure observations. To increase the SNR, the CCD is operated in 2×2 binning mode, resulting in 512×512 pixel images.

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Compared with conventional FPIs employing air-spaced etalons, the SEFPI is more compact and lightweight. The main components, excluding the CCD detector, are enclosed within an insulated aluminum housing to reduce the impact of ambient temperature fluctuations. Thermal insulation, not shown in panel (b) of Figure 1, is installed beneath the sky scanner to shield the instrument from direct sunlight during the daytime and limit heat transfer through the optical dome. Furthermore, a fan continuously circulates air across the dome surface to prevent nocturnal dew formation.

Table 1. System specifications of the SEFPI

Symbol	***Description***	***Specifications***
A	Sky scanner	Φ = 120 mm, Pointing accuracy of ±0.013°
B	Incident light tube	L = 200 mm, Φ = 110 mm, FoV = 2.5º
C	Optical coupling box	Optical spectral wedge (T/R = 0.05 : 0.95) Mirror (R≥97%@450-700 nm)
D	Laser scattering tube	L = 200 mm, Φ = 100 mm
E	Baffle	L = 250 mm, Φ = 75 mm, FoV = 2.5º
F	Interference chamber	Optical bandpass filter (Φ = 75 mm, FWHM = 2.0 nm, center wavelength of 630.0 nm) Solid etalon (Φ = 70 mm, d = 16 mm, n = 1.457, R = 0.79, surface flatness: λ/100) PID controller (Set temperature of 30℃ with a stability better than ±0.005℃)
G	Focusing lens assembly	f = 300 mm, Φ = 100 mm
H	CCD detector	Princeton Instruments, PIXIS: 1024B_eXcelon 1024 × 1024 pixels, 13.312 mm × 13.312 mm

Figure 2 presents representative interferograms obtained by the SEFPI. Panel (a) shows the fringe pattern generated by a 632.8 nm frequency-stabilized He-Ne laser for system calibration, whereas panel (b) shows the interference pattern produced by the 630.0 nm atomic oxygen red-line nightglow emission. The integration times were 30 and 300 seconds for the laser calibration and red-line emission observations, respectively. Seven concentric interference rings are visible in both cases, providing sufficient spectral information for wind and temperature retrieval. The color bar on the right shows the 16-bit pixel grayscale intensity values of the CCD pixels.

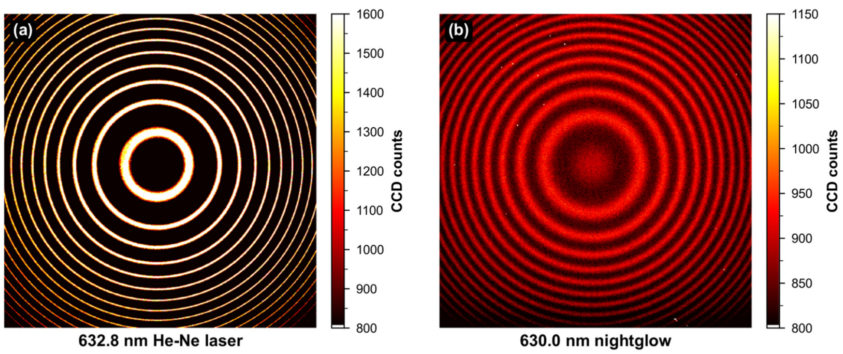

Figure 2. Interferograms observed by the SEFPI. (a) Calibration fringe pattern obtained using a 632.8 nm He-Ne laser with a 30 s exposure. (b) Nightglow fringe pattern of the 630.0 nm atomic oxygen red-line emission with a 300 s exposure.

3 Retrieval algorithm for wind and temperature from the interferogram

Various techniques have been developed to retrieve atmospheric winds and temperatures from FPI measurements. These include Gaussian fitting, Fourier series fitting, and nonlinear regression methods (Harding et al., 2014; Killeen and Hays, 1984; Makela et al., 2011; Shiokawa et al., 2003). Before retrieval, the raw images are preprocessed to improve the effective SNR and reduce computational complexity, following the procedure described by Makela et al. (2011). In this study, the nonlinear regression method proposed by Harding et al. (2014) is adopted to retrieve atmospheric winds and temperatures from the

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measured interference fringes. Given that the SEFPI utilizes a solid etalon rather than an air-spaced etalon, the instrument function developed for air-spaced etalon FPIs cannot be directly applied. Accordingly, the forward model is reformulated to account for the solid medium, and only the final form of the modified retrieval equations is presented below.

The instrument function for the solid etalon, derived from the Airy function, is given by,

$$\tilde{A}(r,\lambda)=\int_0^{r_m} b(s,r)\cdot\frac{I_0\left(1+I_1\left(\frac{s}{r_m}\right)+I_2\left(\frac{s}{r_m}\right)^2\right)}{1+\frac{4R}{(1-R)^2}\cdot\sin^2\left(\frac{2\pi n t}{\lambda}\cdot\sqrt{1-\frac{\sin^2(\theta(r))}{n^2}}\right)}ds \qquad (1)$$

Here, λ denotes the nightglow emission wavelength, r represents the radial distance of the fringes, and s is a dummy variable corresponding to r. R, n, and t refer to the reflectivity, refractive index, and thickness of the solid etalon, respectively. $\theta(r)$ is the angle between the interference fringes and the optical axis, while r_m represents the maximum fringe radius. I_0, I_1, and I_2 are constant coefficients. Finally, $b(s,r)$ is the point-spread function characterizing optical defects, as defined in Harding et al. (2014).

The system parameters are determined by minimizing the residuals between the model for Eq. (1) and the calibrated laser interference fringes using the Levenberg-Marquardt algorithm (Marquardt, 1963). Subsequently, the instrument function is convolved with the nightglow source spectrum to generate the modeled interference pattern of nightglow.

$$Y(r)=\int_{\lambda_0-\delta\lambda_0/2}^{\lambda_0+\delta\lambda_0/2}\tilde{A}(r,\lambda)E(\lambda)\mathrm{d}\lambda+B_{ccd} \qquad (2)$$

where λ_0 is the central wavelength of nightglow emission, $\delta\lambda_0$ represents the free spectral range (FSR), and B_{ccd} is the CCD detector bias.

In Eq. (2), $E(\lambda)$ is a Gaussian emission profile defined as,

$$E(\lambda)=B_{sky}+\frac{B_{line}}{\sqrt{2\pi}\cdot\Delta\lambda}\cdot exp\left(-\frac{1}{2}\frac{(\lambda-\lambda_c)^2}{\Delta\lambda^2}\right) \qquad (3)$$

B_{sky} denotes the background sky emission intensity, and B_{line} represents the nightglow emission intensity. λ_c is the wavelength of the Doppler-shifted nightglow observed by the SEFPI.

$$\lambda_c=\lambda_0\left(1+\frac{v_{los}}{c}\right) \qquad (4)$$

$\Delta\lambda$ denotes the Doppler broadening of the emission line, which is related to the atmospheric temperature.

$$\Delta\lambda=\frac{\lambda_0}{c}\sqrt{\frac{kT}{m}} \qquad (5)$$

In Eqs. (4) and (5), v_{los} represents the line-of-sight wind velocity, and T denotes the temperature. c, k, and m are the speed of light, the Boltzmann constant, and the mass of the emitting species, respectively. By combining Eqs (1)-(5), the optimal values for line-of-sight wind and temperature are derived by minimizing the residuals between the modeled and observed nightglow interference fringes using a weighted least-squares method.

4 Calibration and validation of SEFPI

To calibrate the SEFPI system and validate its wind measurement performance, an acousto-optic frequency shifter (AOFS) was employed to generate controlled Doppler shifts and thereby simulate known wind velocities in the laboratory. In contrast to conventional retroreflective discs, this static device, modulated by radio frequency signals, offers superior accuracy for wind velocity simulation (Langille et al., 2013; Zhu et al., 2023). Figure 3 illustrates a schematic of the experimental setup for measuring Doppler shifts generated by the AOFS with the SEFPI. A frequency-stabilized He-Ne laser, operating at a wavelength of 632.8 nm, emits a beam that first traverses an optical isolator to suppress back reflections. The beam subsequently enters a beam splitter (BS), which divides it into two distinct optical paths. One path is directed to the SEFPI for system calibration after sequential reflection from mirrors M1 and M2. The second beam is focused by lens L1 and directed

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onto the AOFS crystal at an incident angle of 0.6°. Finally, the first-order diffracted beam from the AOFS passes through a pair of lenses (L2 and L3) and a diffuser, forming a uniform collimated beam that fills the SEFPI FoV. The simulated wind velocity V is related to the AOFS modulation frequency F by,

$$V = \frac{c\lambda_0 F}{\lambda_0 F + c\times 10^3} \tag{6}$$

Here, λ_0 is the laser wavelength, c is the speed of light.

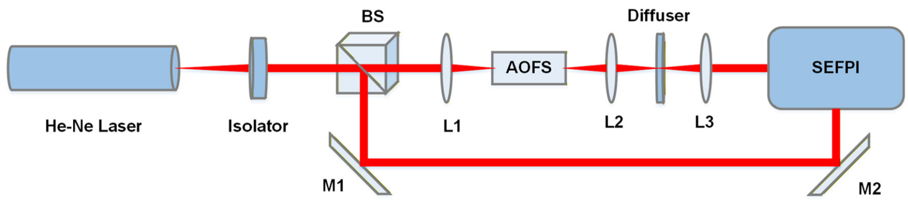

Figure 3. Schematic of the experimental setup for measuring Doppler shifts with the SEFPI using an AOFS. BS: beam splitter; L1-L3: focusing lenses; M1, M2: mirrors.

Initially, a dark frame image was acquired to correct subsequent CCD images during wind velocity measurements. For each simulated wind velocity, ten measurements were performed with an integration time of 5 seconds per measurement. A system calibration was performed before each wind velocity measurement. The AOFS driving frequency was varied from 100 to 200 MHz, corresponding to simulated wind velocities from −63.28 m/s to −126.56 m/s. The negative sign indicates the direction of incident light relative to the acoustic wave propagation in the crystal. The frequency was incremented by 4 MHz steps, resulting in 26 distinct settings across the full range. The AOFS has a frequency uncertainty of ±4 kHz, which is negligible compared with the ±2 MHz frequency stability of the laser over one hour.

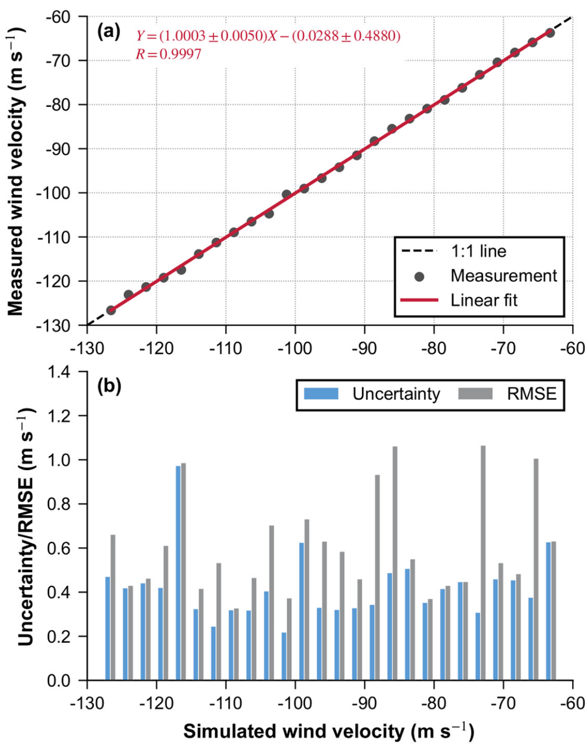

Figure 4. Experimental results of SEFPI wind measurements using Doppler shifts simulated by the AOFS. (a) Measured versus simulated wind velocities; (b) Measurement uncertainty and root mean square error (RMSE) derived from ten repeated measurements at each wind velocity.

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Figure 4(a) compares the measured and simulated wind velocities, while Figure 4(b) presents the corresponding wind uncertainties (sky blue bars) and root mean square errors (RMSEs; gray bars) for each simulated wind velocity. The black dashed line represents the 1:1 reference line, corresponding to a perfect agreement between the measured and simulated wind velocities. Gray dots denote the average measured velocities from ten repeated measurements, and the red line represents the linear regression fit. The measured wind velocities exhibit excellent agreement with the simulated values. Linear regression yields a slope of 1.0003, an intercept of −0.0288 m/s, and a correlation coefficient (R) of 0.9997, demonstrating the SEFPI's high measurement accuracy in the laboratory. Furthermore, both the estimated uncertainty and RMSE for each simulated wind velocity remain below 1.1 m/s. Across 26 velocity points, the average values for wind uncertainty and RMSE are 0.42 m/s and 0.61 m/s, respectively.

5 Cross comparison of field measurements of SEFPI

Field observations were conducted at the Siziwang (SIZW) station (geog.: 41.5°N, 111.7°E; geom.: 36.9°N) in the north of China. To detect faint nocturnal atomic oxygen red-line emissions, the SEFPI integration time was set to 300 s per observation to ensure a sufficient SNR. Before analyzing the horizontal wind measurements of the SEFPI, the reliability of the retrieved wind zero point was evaluated using zenith observations. Analysis of quality-controlled zenith vertical wind measurements from 36 effective nighttime observations showed no appreciable systematic offset from zero (see Appendix, Figure A2).

A Dual-Channel Optical Interferometer (DCOI) had been deployed at this site as part of the Phase II network of the Chinese Meridian Project (CMP) (Wang et al., 2024). The DCOI, an Asymmetric Spatial Heterodyne Spectroscopy (ASHS) interferometer, derives neutral winds at altitudes of approximately 96 km and 250 km by simultaneously observing atomic oxygen emissions at 557.7 nm and 630.0 nm. The instrument has a temporal resolution of 26 minutes; further technical details and measurement validations are available in Liu et al. (2025), Wei et al. (2020), and Zhu et al. (2023).

Given that neutral temperature measurement is not currently implemented in the DCOI systems, an FPI deployed at the Xinglong (XLO) station (geog.: 40.2°N, 117.4°E; geom.: 35.2°N) was selected for an independent intercomparison to evaluate the temperature measurement performance of the SEFPI (Wu et al., 2014; Yuan et al., 2010). The two sites are separated by approximately 502 km. Established during Phase I of the CMP, the XLO station was the first site within China's ground-based airglow observation network to be equipped with an FPI (Wang, 2010; Xu et al., 2021). This instrument, equipped with a fixed air-spaced etalon with a diameter of 100 mm, is designed as a three-channel system measuring OH emission at 892.0 nm (~87 km) and atomic oxygen emissions at 557.7 nm (~97 km) and 630.0 nm (~250 km) (Jiang et al., 2021; Wei et al., 2024). A complete observation cycle of the three airglow channels requires 31 minutes. Further details regarding this FPI instrument at the XLO station can be found in Li et al. (2021), Trondsen et al. (2019), and Vasilyev et al. (2017).

5.1 Wind measurement comparison

Figures 5 and 6 show a daily comparison of horizontal winds at an altitude of 250 km, measured by three instruments from March to May 2024. Figure 5 compares the SEFPI and DCOI measurements, whereas Figure 6 compares the SEFPI and FPI measurements. Note that the error bars in the daily comparisons represent measurement uncertainty rather than the actual wind errors. Due to differences in interferometric configuration and wind retrieval methodology, the measurement uncertainties differ between the DCOI and SEFPI. Specifically, the SEFPI has a simpler optical configuration, and its wind retrieval is based on direct fitting of the measured interference fringes. In contrast, the DCOI employs a more complex optical system and retrieves wind from phase variations extracted from the interferograms using a windowed Fourier transform method. Consequently, DCOI wind retrieval is more sensitive to the fringe contrast and SNR. Overall, the meridional and zonal wind components measured by the SEFPI show good agreement with those measured by both the DCOI at SIZW and the FPI at

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XLO. Nevertheless, quantitative discrepancies are observed, especially under low SNR conditions around local midnight, with maximum absolute differences occasionally reaching ~53.39 m/s relative to the DCOI and ~59.00 m/s relative to the FPI.

Furthermore, all three instruments consistently captured the nocturnal temporal variations of thermospheric winds. Meridional winds typically flow southward, intensifying from dusk to midnight, peaking around midnight, and weakening towards dawn. Zonal winds generally reverse from eastward to westward between 14:00 and 20:00 UT. The timing of the zonal wind reversals is generally consistent within a given month but varies across months, consistent with the results reported by Jiang et al. (2018). Notably, the zonal winds observed on April 26 and May 2, 2024, differed significantly from the typical daily variations. Specifically, following the reversal at 14:00 UT, the westward wind strengthened rapidly and peaked around 18:00 UT. This phenomenon was observed at both SIZW and XLO, with peak magnitudes of approximately 132.70 m/s (April 26) and 196.42 m/s (May 2).

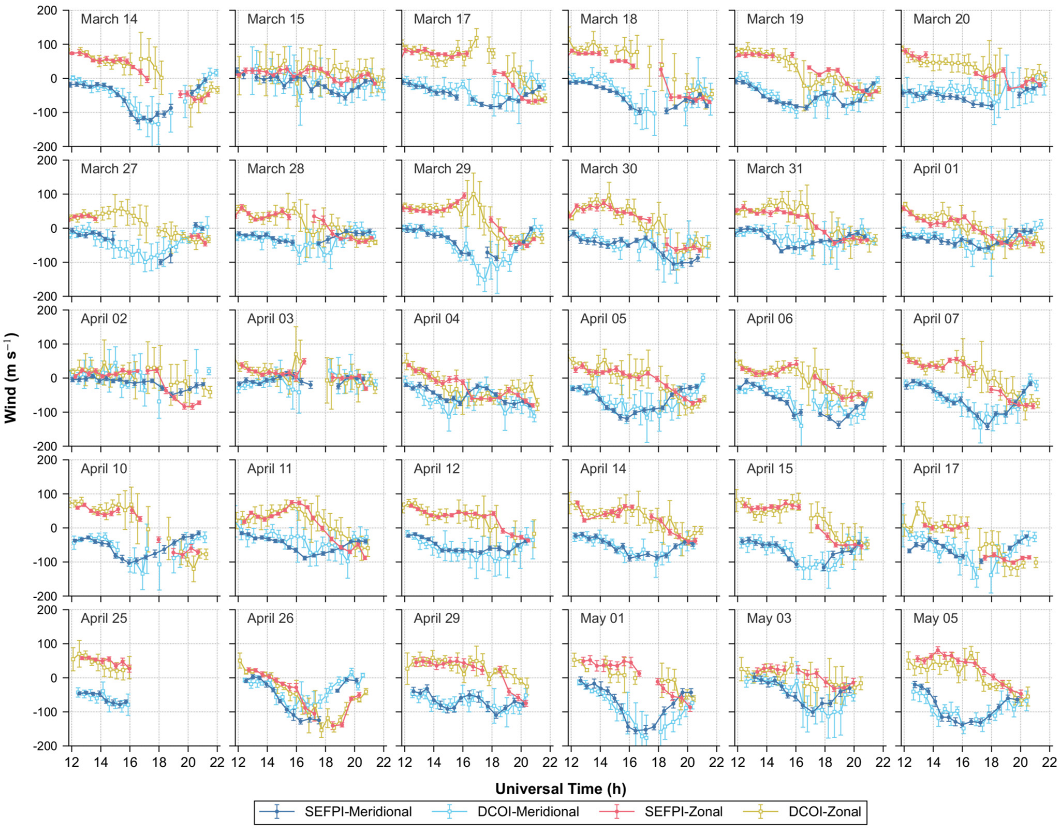

Figure 5. Daily comparison of wind measurements from the SEFPI and DCOI deployed at the SIZW station. Blue and pink solid circles denote the meridional and zonal winds measured by the SEFPI, respectively, while sky-blue and yellow hollow squares represent the corresponding DCOI measurements.

To quantify the discrepancies between the instruments, statistical comparisons were performed between the horizontal wind components measured by the SEFPI and those measured by the DCOI at SIZW and the FPI at XLO. Figure 7 presents scatter plots comparing SEFPI wind measurements with DCOI and FPI measurements for the meridional (panels a and c) and zonal (panels b and d) components. At SIZW, the SEFPI and DCOI exhibit strong linear correlations, with correlation coefficients of R=0.84 for the meridional component and R=0.90 for the zonal component. The best-fit slopes of 1.15 for the meridional component and 1.01 for the zonal component indicate good consistency in wind magnitude. Both meridional and zonal wind components measured by the SEFPI are slightly lower in magnitude than those measured from the DCOI. The mean absolute differences between the DCOI and SEFPI measurements were 1.35 m/s for the meridional component and 2.40 m/s for the

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zonal component, with the standard deviations of discrepancies below 20.50 m/s. The zonal wind measurements exhibit better agreement than the meridional measurements. When the two horizontal wind components are considered tighter, the overall mean absolute difference was 1.88 m/s.

Similarly, comparisons between the SEFPI at SIZW and the FPI at XLO reveal good agreement, with a higher correlation for the zonal component (R=0.93) than for the meridional component (R=0.85). The best-fit slopes are 0.88 for the meridional component and 0.89 for the zonal component, both lower than those obtained in the DCOI comparison. The SEFPI measurements were generally lower than the FPI measurements, with an overall mean difference of 5.58 m/s and a standard deviation of the discrepancies below 17.66 m/s. Discrepancies between the SEFPI and FPI wind measurements were larger than those between the SEFPI and DCOI.

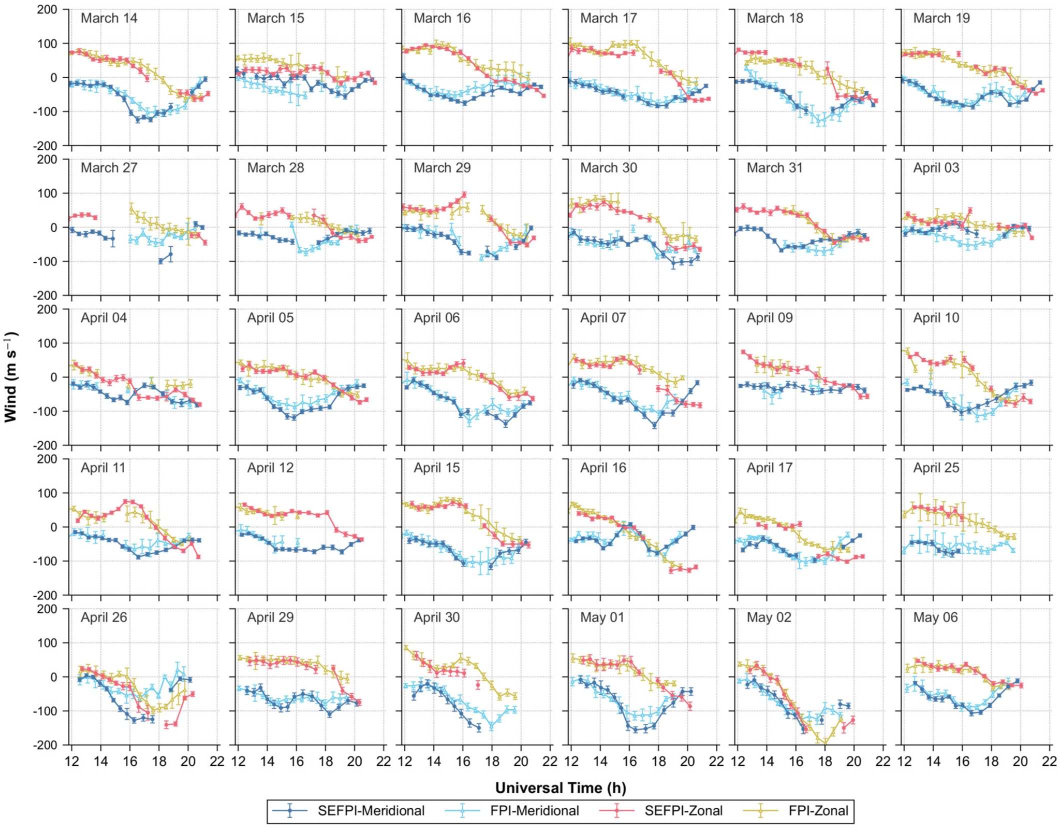

Figure 6. Daily comparison of wind measurements between the SEFPI at the SIZW station and the FPI at the XLO station, following the format of Figure 5. Blue and pink solid circles denote the meridional and zonal winds measured by the SEFPI, respectively, while sky-blue and yellow hollow triangles represent the corresponding XLO FPI measurements.

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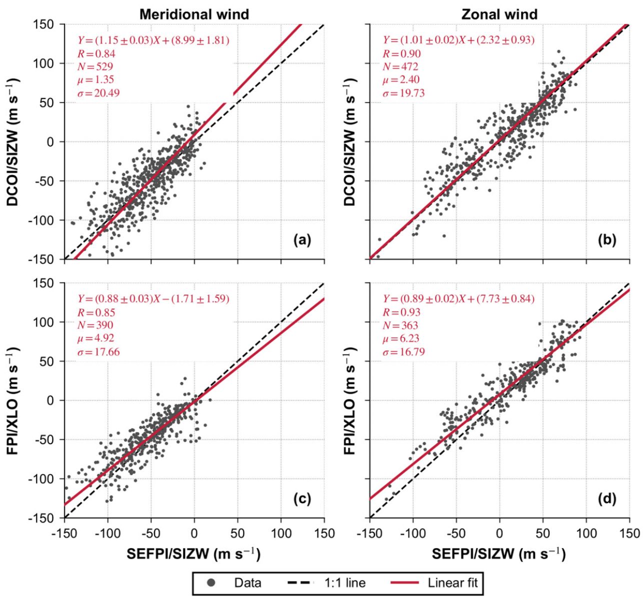

Figure 7. Statistical comparison of horizontal wind measurements. Panels (a) and (b) show the meridional and zonal wind comparisons between the SEFPI and DCOI, respectively, while panels (c) and (d) show the corresponding comparisons between the SEFPI and XLO FPI.

5.2 Temperature measurement comparison

Figure 8 illustrates daily comparisons of thermospheric neutral temperatures measured independently by the SEFPI and FPI over multiple nights from March to May 2024. The plotted temperatures represent averages over five observation directions: the zenith and the four cardinal directions at an elevation angle of 45º. On most nights, the two instruments showed generally consistent temperature variations in both magnitude and temporal evolution. Temperature discrepancies between the two instruments were relatively small from dusk to midnight than during the period from midnight to pre-dawn. The SEFPI and FPI temperature measurements showed close agreement during the first half of several nights, including March 14, 29, and 31 and April 6 and 10. However, the temperatures measured by the SEFPI were generally lower than those measured by the FPI, particularly during the pre-dawn hours. This discrepancy may be associated with the weaker 630.0 nm emission intensity during this period, which reduces the measurement SNR and increases the uncertainty of temperature retrieval (Meriwether et al., 2013). The maximum difference occasionally reaches 232.99 K. In addition, on nights such as April 4, 12, and 16, both the SEFPI and FPI measurements exhibited prominent Midnight Temperature Maxima (MTM) (Adachi et al., 2010; Chiang et al., 2018; Meriwether et al., 2013; Otsuka et al., 2003). Meanwhile, the equatorward meridional wind weakened rapidly but did not reverse direction, as shown in Figure 6.

Scatter plots comparing SEFPI and FPI temperature measurements are shown in Figure 9. Analysis of 384 paired measurements yielded a correlation coefficient of R=0.86, indicating good agreement between the two instruments. The best-fit regression line has a slope of 0.77 and an intercept of 255.72 K, indicating a systematic bias between SEFPI and FPI temperature measurements. The mean temperature difference was 62.38 K, with the SEFPI generally yielding lower temperatures than the FPI. The standard deviation of the temperature differences was 69.89 K.

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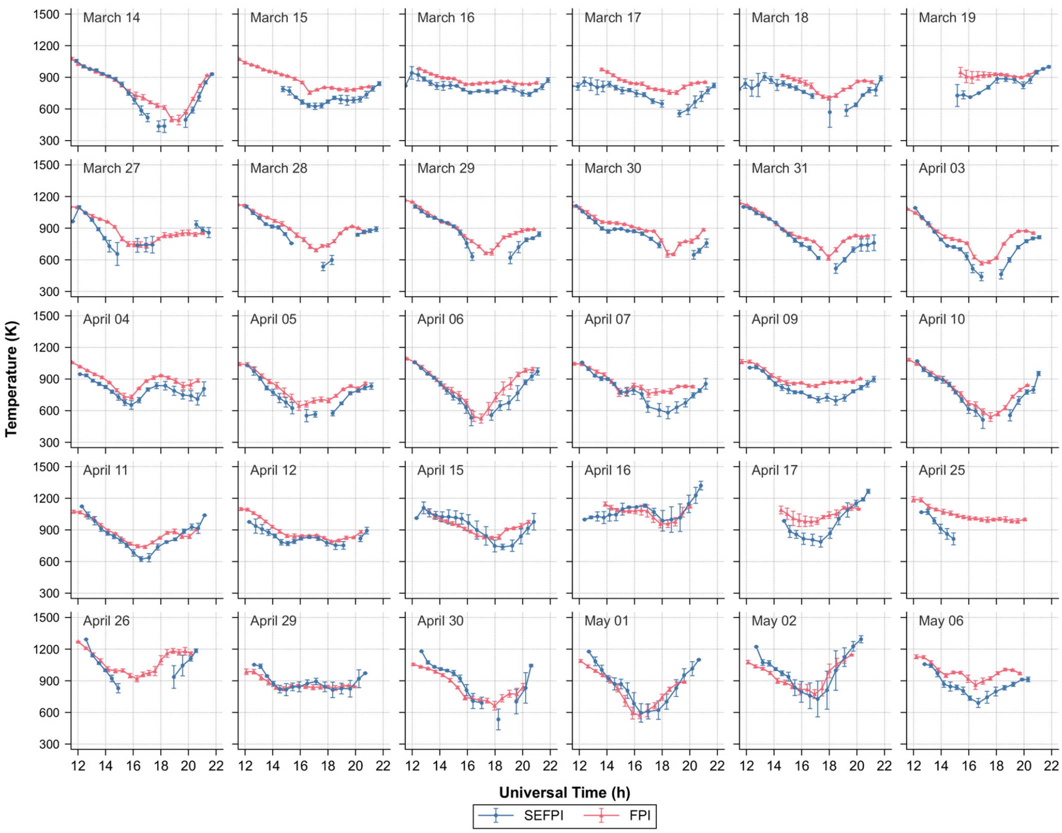

Figure 8. Daily comparison of temperature measurements between the SEFPI at the SIZW station and the FPI at the XLO station, following the format of Figure 6. Blue circles and pink triangles denote SEFPI and XLO FPI measurements, respectively. Each data point represents the average temperature from five observation directions.

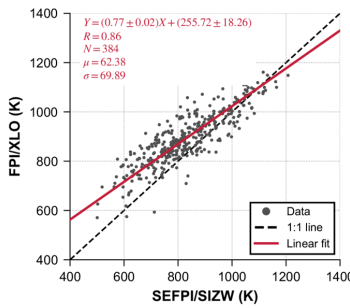

Figure 9. Statistical comparison of temperature measurements between the SEFPI at the SIZW station and the FPI at the XLO station, following the format of Figure 7.

6 Conclusion and discussion

This study presents a novel FPI employing a solid etalon, which successfully measured atmospheric winds and temperatures at an altitude of approximately 250 km from the Doppler shift and spectral broadening of the atomic oxygen red-line emission at 630.0 nm. Compared to conventional FPIs equipped with an air-spaced etalon, the SEFPI is characterized by a more compact and lightweight design. Significantly, it offers a potentially cost-effective solution to large-aperture etalons. Although this solution offers a substantial advancement for upper atmospheric wind and temperature measurements, it also imposes more

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stringent requirements on the thermal stabilization of the solid etalon. The measurement capability of the SEFPI was validated in the laboratory using a newly developed high-precision setup for simulating controlled Doppler shifts. Field performance was further assessed during a 54-day deployment at the SIZW station through cross-comparisons with two independent passive optical instruments.

Laboratory validation demonstrated strong agreement between the measured and simulated wind velocities, yielding a linear regression slope of 1.0003, an intercept of −0.0288 m/s, and a correlation coefficient of 0.9997. These results confirm the high linearity and accuracy of the SEFPI system. Furthermore, wind measurement uncertainty and RMSE remained consistently below 1.1 m/s across the full simulated range, averaging 0.42 m/s and 0.61 m/s, respectively. These uncertainties may ascribe the expected contribution from the He-Ne laser frequency stability of ±2 MHz over one hour, corresponding to a wind velocity uncertainty of approximately 1.26 m/s.

To the best of our knowledge, this study presents the first simultaneous, co-located neutral wind observations at an altitude of 250 km using a solid etalon FPI and an ASHS interferometer. Coincident field measurements conducted from March to May 2024 demonstrate the reliable capability of the SEFPI for thermospheric wind and temperature measurements. Overall, the SEFPI wind measurements exhibit good agreement with those from the co-located DCOI at SIZW and the FPI at XLO. The linear correlation coefficients exceeded 0.84 for both meridional and zonal wind components. Despite this agreement, notable discrepancies of up to ~59.00 m/s occasionally occurred during low SNR conditions near local midnight, highlighting the sensitivity of these instruments to nightglow intensity variability. Moreover, the SEFPI exhibited better agreement with the co-located DCOI than with the FPI at XLO. Considering both horizontal wind components, the overall mean absolute differences of wind measurements in the SEFPI were 1.88 m/s relative to the DCOI and 5.58 m/s relative to the FPI. SEFPI temperature measurements also demonstrate good consistency with FPI data, yielding a correlation coefficient of 0.86. The mean temperature difference was 62.38 K, with the SEFPI reporting slightly lower temperatures than the XLO FPI. On some nights, the temperature differences reached a maximum of 232.99 K, with larger discrepancies generally occurring under weaker 630.0 nm emission conditions.

Several factors may contribute to the observed discrepancies in wind and temperature measurements among the SEFPI, DCOI, and FPI. First, differences in aperture size and optical throughput among the three instruments result in different SNRs for a given integration time. Second, due to differences in observational geometries, the FPI and DCOI sample airglow regions at slightly different locations and spatial volumes (Englert et al., 2012). For example, the SEFPI has a FoV of 2.5°, whereas the DCOI has a FoV of 9° (Liu et al., 2025; Wei et al., 2020). Consequently, at an altitude of 250 km, the corresponding DCOI sampling area is more than 12 times larger than that of the SEFPI. Third, the 502 km geographic separation between the SIZW and XLO stations introduces differences in the local thermospheric and lower atmospheric conditions sampled by the two instruments. Additionally, distinct optical environments at each site may contribute to the observed discrepancies. Finally, spectral contamination from the OH Meinel emission at 629.79 nm is inevitable for FPI measurements of the 630.0 nm emission, particularly around midnight. For single-etalon FPI systems, significant systematic errors can arise when spectral contamination becomes appreciable; Kerr et al. (2023) reported that such errors can become significant when the OH emission brightness exceeds approximately 1/30 of the OI 630.0 nm emission intensity. Notably, the bandwidth of the bandpass filters used in the FPI (~0.8 nm) is significantly narrower than that of the SEFPI (~2.0 nm). Therefore, the SEFPI is more susceptible to OH contamination than the XLO FPI, particularly during periods of weak OI 630.0 nm emission. This difference in susceptibility may therefore contribute to the significant temperature discrepancies observed between the two instruments around midnight.

In conclusion, the SEFPI demonstrated robust measurement capabilities, achieving accurate wind measurements in laboratory validation and showing good agreement with coincident field observations. Given its compact design and cost-effectiveness, the SEFPI is well-suited for the development of ground-based observational networks targeting the middle and upper atmosphere. The SEFPI therefore provides a promising approach for expanding observations of neutral winds and

https://doi.org/10.5194/egusphere-2026-2475
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temperatures in the middle and upper atmosphere, although its solid etalon requires stringent thermal stabilization. Future work will focus on co-locating the SEFPI and the XLO FPI at the same site for direct measurement validation, including the use of a narrower bandwidth interference filter to further investigate the observed temperature discrepancies.

7 Appendix

A.1 Thermal stability of the solid etalon during field observations

The thermal stability of the solid etalon is an important factor affecting the long-term stability of the SEFPI, since variations in the etalon temperature can induce changes in its refractive index and physical thickness, thereby altering the instrumental spectral response. To evaluate the thermal stability under actual field-operating conditions, we analyzed the solid-etalon temperature recorded during the nighttime operation of the SEFPI. The dataset includes 36 effective nighttime observation periods. Because the SEFPI was operated only during nighttime airglow observations, the temperature records presented here correspond to the actual operating periods of the instrument.

As shown in Figure A1(a), the measured etalon temperature remained closely centered around the preset temperature of 30 °C throughout the observation campaign, without an evident long-term drift. It is evident from Figure A1 (b) that the corresponding temperature deviation is distributed statistically around zero. The mean temperature deviation was 0.0001 °C, with a standard deviation of 0.0026 °C. These results demonstrate that the PID temperature-control system maintained the solid etalon with high thermal stability during the actual field observations.

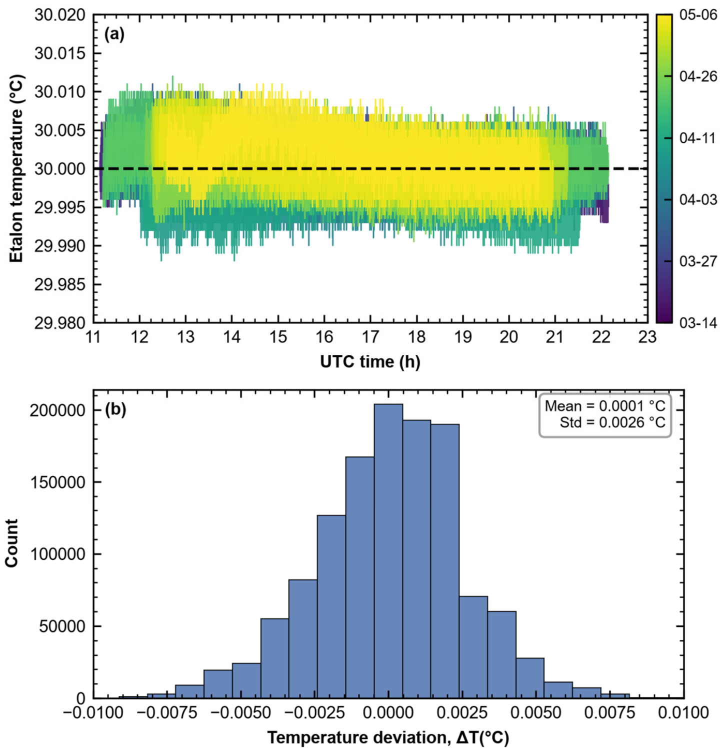

Figure A1. Thermal stability of the SEFPI solid etalon during field observations. (a) Measured solid-etalon temperature during 36 effective nighttime observation periods. The temperature control system sampled the temperature at a rate of one measurement per second. The dashed line indicates the preset temperature of 30 °C, and the color scale represents the observation date. (b) Statistical distribution of the temperature deviation from the preset temperature. The mean deviation and standard deviation are 0.0001 °C and 0.0026 °C, respectively.

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Preprint. Discussion started: 21 August 2026

A.2 Vertical winds for zenith direction during field observations

In the SEFPI field observations, a frequency-stabilized He-Ne laser exposure was acquired immediately before each airglow exposure. The laser measurement was used to characterize the instrumental response and determine the calibration parameters for the subsequent airglow retrieval. The wind and temperature were subsequently retrieved using a nonlinear regression fitting method based on the airglow forward model, which incorporated the instrument system parameters calibrated from each laser measurement.

As an independent check of the wind zero-point, vertical winds for zenith observations obtained during the 36 effective nighttime field campaign were analyzed. A total of 404 quality-controlled zenith vertical wind measurements were retained. As shown in Figure A2(a), the retrieved vertical winds are distributed around zero throughout the observation period. The statistical distribution shown in Figure A2(b) gives a mean vertical wind of -0.19 m/s and a standard deviation of 5.64 m/s. The small magnitude of the mean value and the absence of an evident systematic displacement from zero indicate that no appreciable systematic wind offset.

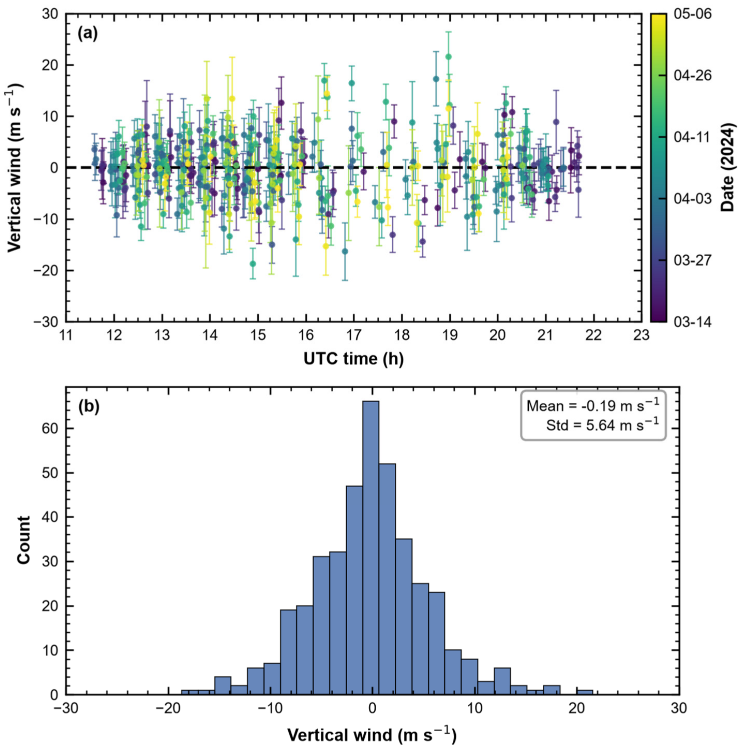

Figure A2. Zenith vertical wind measurements obtained during 36 effective nighttime field observations. (a) Quality-controlled zenith vertical wind measurements. The error bars represent the corresponding wind-retrieval uncertainties, and the dashed line indicates zero vertical wind. Measurements are color-coded according to the observation date. (b) Statistical distribution of the zenith vertical wind measurements. The mean vertical wind is -0.19 m/s, with a standard deviation of 5.64 m/s.

Data availability

The data of DCOI in this paper are available at the Chinese Meridian Project (https://www.meridianproject.ac.cn/en/). The SEFPI data sets for this study can be available in the website link of Wang (2026).

https://doi.org/10.5194/egusphere-2026-2475
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Author contributions

YZ conceptualized the study and contributed to the review and editing of the manuscript. TW was responsible for the experimental design, instrument development, and measurements, as well as data processing and the preparation of the manuscript draft. HG and JX contributed to the review and editing of the manuscript. GZ performed the experimental validation. WL and WY carried out the instrument deployment and field measurements. QG and ZT conducted the etalon tests. All authors have read and agreed to the published version of the manuscript.

Competing interests

The contact author has declared that neither of the authors has any competing interests.

Acknowledgments

All authors appreciate all the funding from the National Key R&D Program of China (2023YFB3905100), the Project of Stable Support for Youth Team in Basic Research Field, CAS (YSBR-018), the National Natural Science Foundation of China (42174212, 62375285), the science and technology innovation Program of Hunan Province (2025RC1047), the Chinese Meridian Project, and the Specialized Research Fund for State Key Laboratory of Solar Activity and Space Weather. We acknowledge the use of data from the Chinese Meridian Project. We sincerely thank all contributors to the development and deployment of the DCOI instruments. We would like to express our gratitude to the staff responsible for the operation and maintenance of the instruments at the SIZW and XLO stations. We are also grateful to the peer reviewers for their constructive comments and helpful suggestions, which greatly improved the quality of the manuscript.

Financial support

This work was supported by the National Key R&D Program of China (2023YFB3905100), the Project of Stable Support for Youth Team in Basic Research Field, CAS (YSBR-018), the National Natural Science Foundation of China (42174212, 62375285), the science and technology innovation Program of Hunan Province (2025RC1047), the Chinese Meridian Project, and the Specialized Research Fund for State Key Laboratory of Solar Activity and Space Weather.

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