



Development and validation of a ground-based Asymmetric Spatial Heterodyne Spectroscopy (ASHS) system for sounding neutral wind in the mesopause region

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Abstract. Winds in the mesopause region are key to understanding atmospheric dynamics. This study presents a novel ground-based Asymmetric Spatial Heterodyne Spectroscopy (ASHS) system designed to measure these winds by observing the nighttime green line airglow of atomic oxygen. The system's configuration, thermal behavior, and calibration procedures are detailed. The as-built configuration meets the performance expectations established during the design phase, enabling wind measurements with an accuracy better than 2 m/s. Field observations from Mohe Station (53.5°N, 122.3°E) during geomagnetically quiet conditions demonstrate good agreement with co-located LiDAR data, validating the ASHS system's capability to derive mesopause winds from interferograms.

Plain language summary.

Winds in the mesopause region (85-100 km altitude) drive upper-atmospheric dynamics and energy transfer. We present the Asymmetric Spatial Heterodyne Spectrometer, a ground-based instrument, to measure winds by observing the green airglow of atomic oxygen. Lab tests demonstrated the instrument achieves <2 m/s accuracy. Field measurements at a high-latitude



site in China showed strong agreement with independent LiDAR data, confirming that the system delivers reliable wind retrievals.

1. Introduction

The Earth's upper mesosphere and lower thermosphere serve as a critical interface where chemical and physical processes are influenced by energy transmission from both the lower
35 atmosphere and near-Earth space (Hedin et al., 1989; Kelly, 2009). Neutral winds are essential for understanding the dynamics, transport, and energy budget in the mesopause region, making them a key parameter in atmospheric models (Christensen et al., 2009; Dhadly et al., 2023).

Over the past few decades, optical passive sounding techniques have become pivotal for
40 precise measurements of neutral winds in the middle and upper atmosphere. Utilizing these techniques, Doppler winds are accurately determined by analyzing airglow emission lines from particles transported by atmospheric winds. Among these instruments, the Fabry-Perot Interferometer (FPI) is particularly noteworthy, providing high-precision Doppler shift measurements using a Fabry-Perot etalon. Equally important is the Michelson Interferometer
45 (MI), which can be field-widened to obtain a high etendue device, delivering outstanding signal-to-noise ratios and detection efficiency. After decades of refinement, both FPI and MI have achieved widespread adoption in ground-based and satellite-based wind measurement applications (Hays et al., 1981; Gualt et al., 1996; Killen et al., 2006; Mclandress et al., 1996). Despite the valuable observations provided by these instrument, neutral wind measurements
50 remain sparse over long-term periods and across wide areas.

A notable variant of the Michelson Interferometer is one that utilizes a technology called Asymmetric Spatial Heterodyne Spectroscopy (ASHS), first proposed in 2007 (Englert et al., 2007). The ASHS is an inherent concept of spatial heterodyne spectroscopy (SHS) by extending the optical path of one interferometer arm to observe interferogram at high optical path



55 differences (OPDs), which allows field-widening technology and interferometric measurements
without moving parts while maintaining spectral resolution. Field-widening refers to modifying
a conventional interferometer to enhance its ability to collect light over a wider field of view
while maintaining its modulation efficiency. One application of this technology is the Redline
DASH Demonstration Instrument (REDDI), which was built to make ground-based neutral
60 wind observation by sounding atomic oxygen red line emission at 630 nm in thermosphere
(Englert et al., 2010). Subsequently, a DASH interferometer, the Michelson Interferometer for
Global High-Resolution Thermospheric Imaging (MIGHTI), was developed for the Ionospheric
Connection Explorer (ICON) satellite to measure neutral winds by observing atomic oxygen
green line emission at 557.7 nm and redline emission at 630.0 nm simultaneously in mesopause
65 and thermosphere at an altitude of 90-300 km (Englert et al., 2017).

The cost-effective and precise ASHS instruments are ideally suited for establishing a
ground-based network for thermospheric neutral wind observations. Compared with traditional
MI, ASHS avoids complex scanning structures. Moreover, in comparison with MI and FPI, it
can synchronously detect calibration spectral lines to mitigate the impact of instrumental drift.
70 Wei et al. (2020) proposed a ground-based, thermally-insensitive monolithic ASHS
interferometer for observing the atomic oxygen airglow at 630.0 nm. This configuration was
verified in the laboratory and demonstrated excellent thermal stability (Dötzer, 2019; Liu et al.,
2018; Wei et al., 2022). The methodology and design tools developed for that instrument are
also adopted in the present work.

75 To the authors' knowledge, existing ground-based ASHS instruments are limited to
observing the atomic oxygen red line in the middle and upper thermosphere. To extend wind
measurements to a lower altitude region, it is advantageous to additionally observe the green
line, which has its intensity peak just above the mesopause at around 96 km and spanning a
layer approximately 10 km thick (Zhang and Shepherd, 2005). Detecting this faint emission



80 from the ground is challenging due to the low layer's thinness. The scattering of artificial light sources in the lower atmosphere can reduce the sensitivity and precision of the detection.

Several ground-based instruments have been developed to measure neutral winds in mesopause region by observing the atomic oxygen green line. For instance, a three-channel FPI has been developed by Wu et al. (2004) to detect the green line in mesopause region. Another
85 instrument is a variant of the Michelson Interferometer, named the E-Region Wind Interferometer (ERWIN II), which facilitates the detection of the green line in mesopause region (Kristoffersen et al., 2013). For a ground-based ASHS system, where constraints such as mass and volume are less critical, combining multiple channels within a single interferometer is less essential. Instead, separate instruments can be individually optimized and tailored to the
90 geometry and radiative properties of their respective emission layers to improve observation quality and temporal resolution.

This work focuses specifically on the design, calibration, and verification of an ASHS instrument dedicated to observing the atomic oxygen green line and is organized as follows: Firstly, the concept of the ASHS interferometer and the principle of wind measurements are
95 described in Section 2. In Section 3, the optical design principle is discussed. In the subsequent section, the ASHS instrument configuration and main parameters are presented. In order to evaluate the performance of the instrument, a thermal stability test and wind measurement calibration are carried out in Section 5. In Section 6, horizontal wind is retrieved from field observations and compared with co-located LiDAR measurements. Section 7 provides a
100 summary of the study.

2. ASHS concept

Fig. 1 illustrates the configuration of a field-widening ASHS interferometer. The incident light is split into two beams by a beamsplitter, which then reflect off two gratings and recombine to form interference fringes, which can be expressed as



105
$$I(x) \propto 1 + V_I(x) \cos[2\pi L(\sigma_0 - \sigma_L)] \exp[-2\pi^2 \sigma_D^2 L^2] \quad (1)$$

where $V_I(x)$ is the visibility function of the interferometer, which is a function of sampling -
position x on the detector, $L = 4 \tan \theta x + 2\Delta d$ is the OPD, θ is the Littrow angle
corresponding to Littrow wavenumber σ_L , σ_0 is the central wavenumber of the emission line,
the term $2\Delta d$ represents the optical path difference between the nominal and extended arms of
110 the interferometer at the Littrow wavelength, and σ_D is the Doppler broadening parameter,
which is defined as

$$\sigma_D = \sigma_0 \sqrt{\frac{k_B T}{mc^2}} \quad (2)$$

where, k_B is the Boltzmann constant, T is the kinetic temperature, m is the mass of the
emitter and c is the velocity of light. The cosine term is the phase of fringe in the interferogram.
115 The exponential term damps the visibility of the interferogram due to Doppler broadening of
the emission lines. Accordingly, the phase term of fringes in the interferogram can be described
as a function of the sampling position x

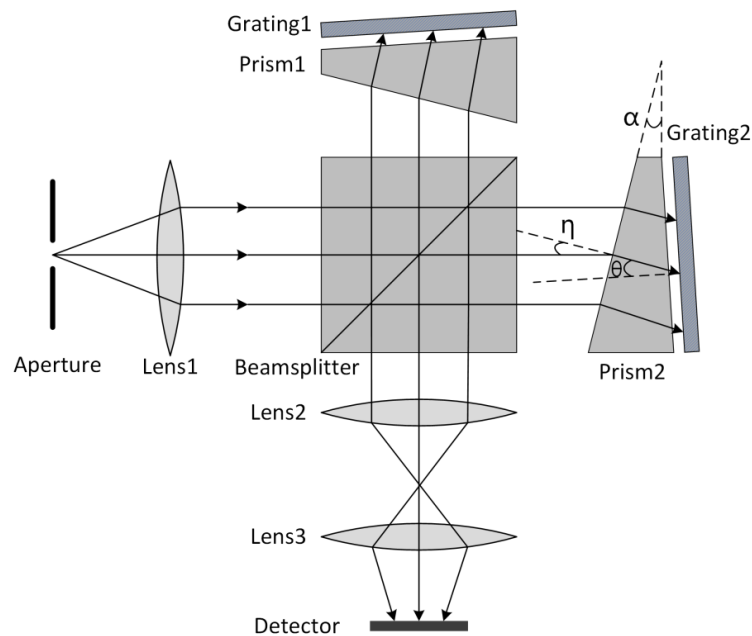
$$\phi(x) = 2\pi(4 \tan \theta x + 2\Delta d)(\sigma_0 - \sigma_L) \quad (3)$$

The phase difference between reference and Doppler-shifted interferograms can be
120 expressed as:

$$\Delta\phi(x) = \phi'(x) - \phi(x) = 2\pi(4 \tan \theta x + 2\Delta d)(\sigma_v - \sigma_0) \quad (4)$$

where σ_v is the Doppler-shifted wavenumber of the emission line. Then the Doppler velocity
 v can be determined from the phase difference $\Delta\phi$ of two observations by

$$v = \frac{\Delta\phi \cdot c}{2\pi\sigma_0(4 \tan \theta x + 2\Delta d)} \quad (5)$$



125

Fig. 1. The configuration of the field-widening ASHS interferometer.

3. Optical design

3.1 Optical layout of ASHS interferometer

The configuration of the ASHS interferometer is similiter to the design of Wei et al. (2020), as
 130 shown in Fig. 2. Here t_0 represents the nominal thickness of the beamsplitter, while t_1 refers
 to the additional asymmetric extension in thickness, t_2 is the thickness of the prism, d_1 and d_2
 are the thickness of spacer 1 and spacer 2, respectively.

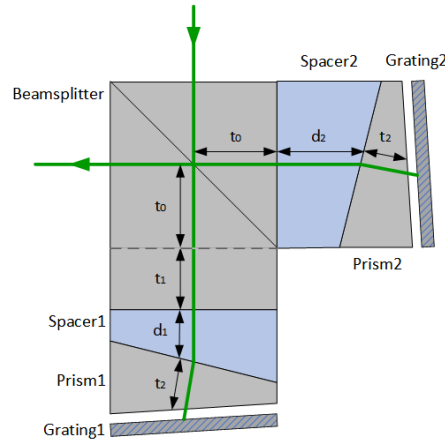


Fig. 2. The configuration of a thermally compensated field-widening ASHS interferometer. The extra optical path is introduced by extending one arm of the beamsplitter.

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3.2. OPD offset

The choice of OPD offset is a balance of the visibility of the fringe pattern and the measurement sensitivity of the instrument. According to Eq. (1) the visibility can be expressed by an envelope function

$$140 \quad \text{Visibility} = V_I(x) \exp(-2\pi^2 \sigma_D^2 L^2) \quad (6)$$

The visibility decreases with the OPD offset L . Conversely, the sensitivity of the ASHS interferometer to wind-induced phase shifts decreases as the OPD offset becomes smaller (see Eq. (5)).

A series of numerical simulations were conducted to determine the optimal OPD offset for
145 measuring winds using the atomic oxygen green line emission at 557.7 nm. The interferogram of the atomic oxygen green line is simulated according to Eq. (1), including background radiation, random noise and transmission efficiency. The Doppler velocity is assumed to be 100 m/s and temperature is 200 K, which is a typical values in the mesopause region. Fig.3 (a) shows the visibility and sensitivity variation when OPD offset is changed from 0 mm to 200 mm. The



150 visibility remains relatively constant up to an OPD offset of 40 mm, then decreases
approximately linearly up to 120 mm, after which it stabilizes again. In contrast, the phase
difference decreases linearly across the entire simulation range. By retrieving Doppler velocity
from the phase difference, the wind measurement error corresponding to OPD offset can be
estimated as shown in Fig. 3 (b). There are four lines representing wind retrieval errors under
155 four different visibility conditions, with each line being the result of a Monte Carlo simulation
with 10,000 samples. The wind uncertainty decreases rapidly from an OPD offset of 0 to 50
mm, forms a wide trough between 50 and 90 mm, and then increases again for larger OPD
offsets. To minimize instrument size while reducing wind estimation error, an OPD offset of 55
mm in air was selected as the baseline for the new instrument based on these simulation results.

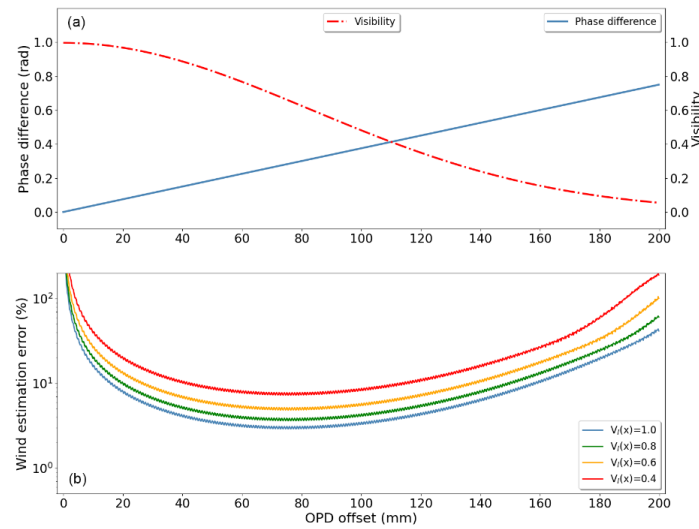


Fig. 3. (a) The visibility and sensitivity response to OPD offset. (b) The error of wind retrieval in different OPD offset. Each line is an average of Monte Carlo simulation with 10,000 samples.

$V_I(x)$ is the visibility function as described in Eq. (1).

3.3. Field-widening

165 Fringe contrast in a Michelson interferometer typically decreases at larger field angles, but this



issue can be mitigated by applying field-widening technology in an ASHS system. The fringe intensity of on-axis ray is discussed in Eq. (1). When solid angle of the incident illumination is Ω_m , the fringe intensity Eq. (1) can be rewritten as

$$I(x) = \Omega_m \int_{-\infty}^{+\infty} B(x) d\sigma \left\{ 1 + \operatorname{sinc} \left(\frac{4 \tan \theta \sigma x + \sigma \Delta d(\omega)}{2} \Omega_m \right) \right. \\ \left. \cos 2\pi \left[4 \tan \theta \left(\sigma - \sigma_L - \frac{\Omega_m \sigma}{4\pi} \right) x + \sigma \Delta d(\omega) \left(2 - \frac{\Omega_m}{4\pi} \right) \right] \right\} \quad (7)$$

When $\Omega_m = \frac{\pi}{4 \tan \theta \sigma x + \sigma \Delta d(\omega)}$, the maximum amplitude of $I(x)$ is achieved (Liu et al., 2018).

That means the field of view is limited by the spatial frequency and extended distance $\Delta d(\omega)$.

The influence of incident light at different angles on spatial frequency can be eliminated by inserting the prisms to enlarge the field of view. When the minimum deviation in the prism occurs the incident angle is η . The relationship between the incident angle and Littrow angle θ of the gratings is

$$2(n^2 - 1) \tan \eta = n^2 \tan \theta \quad (8)$$

where n is the refractive index of the prism (Harlander, 1991). The apex angle α of the prisms can be determined by the relationship,

$$n \sin \frac{\alpha}{2} = \sin \eta \quad (9)$$

It should be noted that the extended distance $\Delta d(\omega)$ depends on the incident angle ω .

According to Eq. (7) of Wei et al. (2020), the difference of OPD for rays in different incident angles can be compensated when the higher order term is set to zero, i.e.,

$$\frac{t_1}{n_1} + d_1 - d_2 = 0 \quad (10)$$

The field-widening is achieved when the configuration complies with both Eq. (9) and Eq. (10).

A ray-tracing optimization approach is applied in this study to determine the parameters, which minimizes the phase difference between the on-axis and off-axis rays by iterating parameters of prisms, spacers and asymmetric thickness of the beamsplitter.



3.4. ASHS interferometer configuration and optimization

190 The monolithic ASHS interferometer is constructed from different types of glass, each with
unique thermal expansion properties, making it sensitive to changes in the ambient environment.
The thermal sensitivity of these optical components can lead to phase drift and visibility
deterioration in the interferograms. Careful selection and combination of materials minimize
this sensitivity to achieve an optimal thermal design, the derivatives of both the phase and OPD
195 with respect to temperature must be minimized:

$$\frac{d\phi(x)}{dT} = 2\pi \left(\frac{df_x}{dT} x + 2 \frac{d\Delta d}{dT} \sigma \right) = 0 \quad (11)$$

where T is the temperature, $f_x = 4 \tan \theta (\sigma_0 - \sigma_L)$ is the spatial frequency. This equation
holds when the two terms of the derivative, $\frac{df_x}{dT}$ and $\frac{d\Delta d}{dT}$, are equal to zero at the same time
(Wei, 2021).

200 Ray-tracing software is applied to optimize the ASHS interferometer configuration by
considering restrictions of the OPD offset, field-widening and thermal compensation, etc. The
final optimization parameters for measuring the atomic oxygen green line emission are given in
Table 1.



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Table 1. Specification of ASHS Interferometer

Interferometer	OPD offset	55 mm
	Spatial frequency	16.67 cm ⁻¹ (557.7 nm)
	Gratings	groove density: 900 mm ⁻¹
		Material: Fused silica
		Littrow angle: 14.55°
	Beamsplitter	Material: CDGM H-K9L
		Asymmetric Beamsplitter
	Field-widening prism	Material: Schott N-Lak12
		Apex angle: 13.29°
	Spacers	JGS1 (Spacer 1), CDGM D-FK61 (Spacer2)

4. ASHS instrument configuration

The configuration of the ASHS instrument is depicted in Fig. 4, with component information provided in Table 2. In addition to the ASHS, the complete instrument includes front optics that
210 image the atmospheric scene onto the gratings and camera optics that image the gratings onto the focal plane array, which are designed separately. Within the front optics, a beamsplitter overlays the atmospheric scene with light from a krypton lamp, which is used to monitor instrument drifts. Furthermore, a mirror system is installed between the instrument and the atmosphere, allowing observations in different directions and enabling zenith direction viewing
215 to obtain zero wind measurements.

The M1, M2 mirrors are installed on a two-axis all-sky scanning system to collect airglow radiation in 45° elevation and zenith directions. The telescope L1 to L2 and the aperture stop



are designed with a full field of view of 9° to ensure high luminous flux and signal-to-noise ratio of the instrument. The calibration line ($\lambda = 557.029$ nm) from a krypton lamp is attenuated
220 by neutral density filter ND to an intensity that is comparable to the atomic oxygen green line. The collimated and holographically diffused calibration line is transmitted on a beamsplitter BS1 and enters the relay lens. The airglow and the calibration signal, collimated by relay lens L4 to L5, both enter the interferometer and produce fringe images. F1 is a narrow band filter with a center wavenumber of 557.7 nm and a band width of 2 nm, so that background radiation
225 and other spectral lines of the krypton lamp are suppressed.

The double telecentric system L6 to L7 with a magnification of 1.0 relays the fringe pattern from the localization plane of the interferometer to the focal plane of the detector. The 2048×2048 pixels weak signal detector with a pixel size of 13.5 μm acquires images in an area of 27.6×27.6 mm. To increase rigidity and reduce system deformation, the interferometer,
230 telecentric system, and detector have been installed on a thick aluminum alloy plate. Additionally, a metal shell has been added to the plate. The components in dashed line in Fig. 4 are integrated into an insulation box made of insulation board covered with aluminum film so that the interferometer and optical systems are prevented from impacting by rapidly changing ambient environment.

235 The interferometer is integrated into an active temperature-controlled thermostat, which includes an aluminum container, a polystyrene insulating enclosure, a set of heating tapes, a set of temperature sensors, and a PID (proportional-integral-derivative) controller. Enclosure windows W1 and W2 are installed at the entrance and exit positions. Temperature sensing is completed by platinum resistors and thermistors and a target temperature at 30 $^\circ\text{C}$ is set and
240 maintained by the PID controller. The whole temperature-control system keeps the temperature stability inside the aluminum container better than ± 0.1 $^\circ\text{C}$.

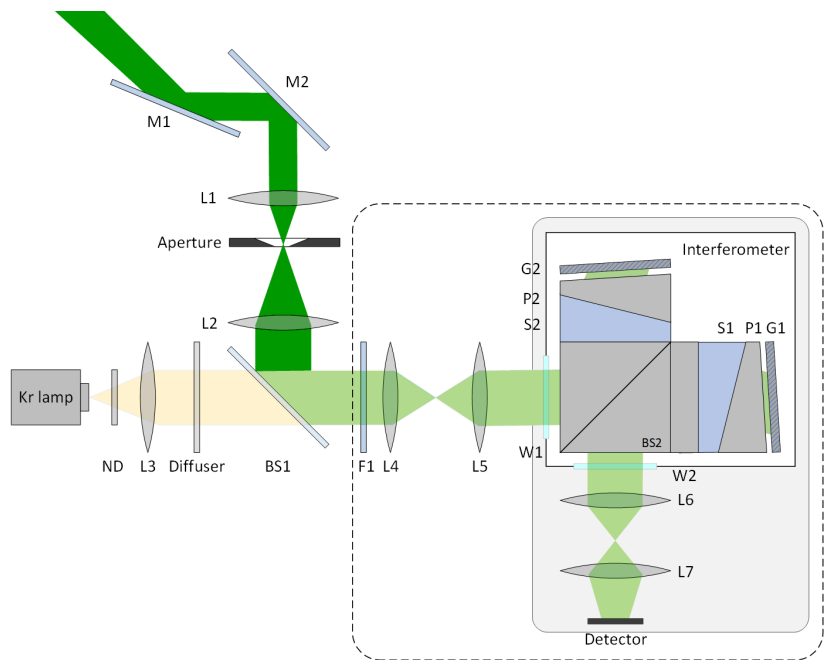


Fig. 4. The configuration of the ASHS instrument.

Table 2. Major Parameters of the Instrument Components

Instrument components	Major element	Parameter
Optical system	Full field of view	9°
	Etendue	0.156 cm ² steradian
	Relay lens magnification	1.0
	Center wavelength of the filter	557.7 nm
	Band width of the filter	2 nm
Detector	Size	2048×2048
	Pixel length	13.5 μm
Calibration illuminant	Illuminant wavelength	557.029 nm
	Neutral density filter	OD 0.8

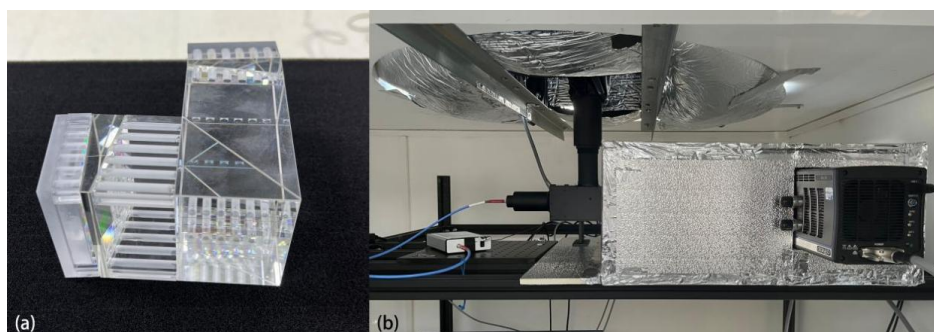


Fig. 5. The monolithic ASHS interferometer (a) and assembled ASHS instrument (b). All spacers are made into a hollow structure to reduce the thermal expansion.

5. Laboratory calibration

250 5.1. Thermal performance

Although the ASHS was designed to be highly thermally stable, as described in Section 3.4, the as-built configuration may exhibit some unintended thermal sensitivity due to manufacturing tolerances in the components and the assembly process. The use of UV-curing bonding layers, whose thickness is intended to compensate for component tolerances, can affect the thermal performance as well. Therefore, it is indispensable to verify the as-built thermal stability of the interferometer.

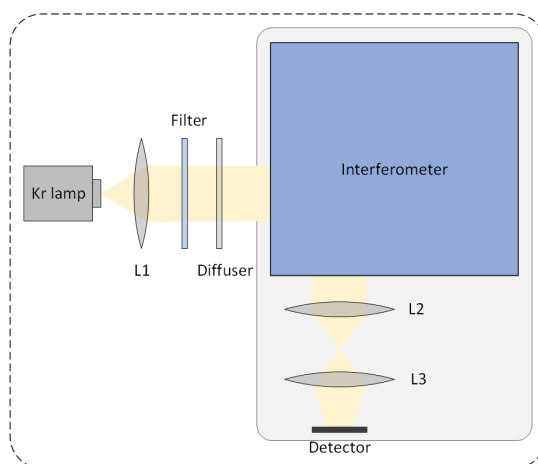




Fig. 6. The configuration of thermal performance test.

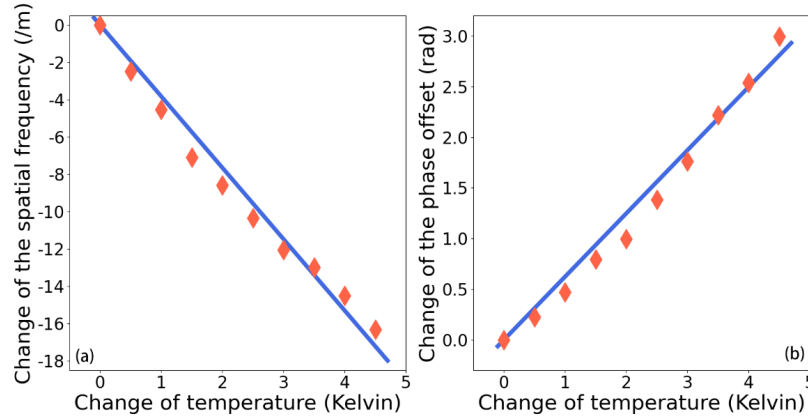


Fig. 7. The sensitivity of spatial frequency (a) and phase offset (b) when the temperature changes from 25.5 °C to 30 °C.

Fig. 6 is a setup for thermal performance test based on the instrument configuration in Section 4. The illumination system, temperature-controlled interferometer and imager are encapsulated in an insulation housing, which prevents air exchange with the external environment. The ambient temperature is set at 24 °C through the air conditioning system. The interferometer was thermally regulated using the PID controller within a temperature range of 25.5 °C to 30 °C in 0.5 °C increments. Every four hours, when the temperature was stable, frames of the interferograms are continuously sampled for half an hour, with each exposure time of 30 seconds. After darkfield, flatfield and phase distortion correction for each interferogram, the phase was extracted by the following equation,

$$\phi(x) = \tan^{-1} \left\{ \frac{\Im[I_D(x)]}{\Re[I_D(x)]} \right\} \quad (12)$$

where $\Im[I_D(x)]$ and $\Re[I_D(x)]$ are the imaginary part and real part of the signal-modulated portion, respectively. The phase of the center 1600 pixels was fitted linearly using the least squares method. The slope of the fitted line divided by 2π is taken as the spatial frequency and the intercept is taken as the phase offset.

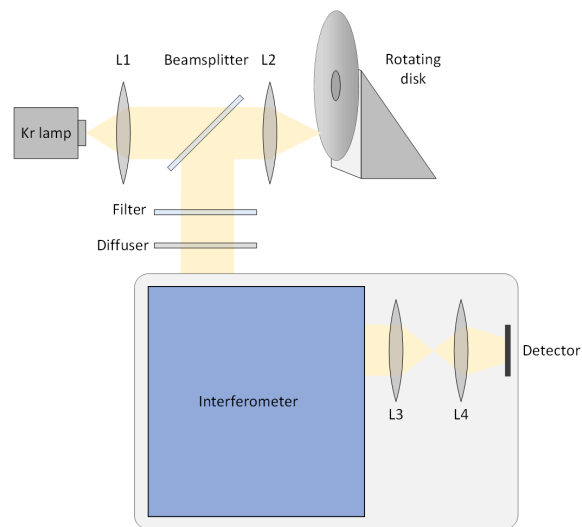


Fig. 7 shows the response of spatial frequency and phase offset to the change of temperature. Each point represents the average of approximately 44 measurements. The solid lines are the result of a linear least squares fitting. The spatial frequency and the phase offset are linearly correlated with temperature, which are $-0.038 \text{ cm}^{-1}/^{\circ}\text{C}$ and $0.624 \text{ rad}/^{\circ}\text{C}$,
280 respectively. This temperature sensitivity is sufficiently small that it does not impact wind data quality, provided that a calibration line is measured synchronously, as implemented in this instrument (Harlander et al., 2010).

5.2. Doppler velocity calibration

To verify the key as-built instrument parameters and to characterize the instrument prior to field
285 deployment, laboratory calibration is indispensable. Specifically, according to Eq. (5), the OPD may deviate from the design value during manufacturing and UV-curing, which introduces system errors in the wind retrieval from phase difference (Zhu et al., 2023).

A Doppler-shift generator is established as shown in Fig. 8. A krypton lamp is used for illumination. The light is focused onto a high-speed rotating disk covered with retroreflective
290 film, which reflects the light back along its original path. This reflected light is then directed by a beamsplitter into the interferometer. A narrow band filter is applied to select krypton emission line at 557.029 nm entering the interferometer. The disk is driven by an electric motor which is set at $1000\text{-}5000 \text{ RPM}$ (revolutions per minute) corresponding to a Doppler velocity of $18.6\text{-}93.1 \text{ m/s}$. Ten frames of interferograms are recorded for each speed in the experiment. As the
295 reflection of light significantly decreases when the disk is not rotating, the first ten frames at 1000 RPM serve as a baseline, representing a condition analogous to the zenith overhead wind. This approach ensures that the signal-to-noise ratio (SNR) remains uniform across all frames. After image correction and phase extraction, the phase difference is obtained by subtracting the baseline from an average phase of ten frames of interferogram at different speeds.



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Fig. 8. The configuration of laboratory calibration for the ASHS instrument.

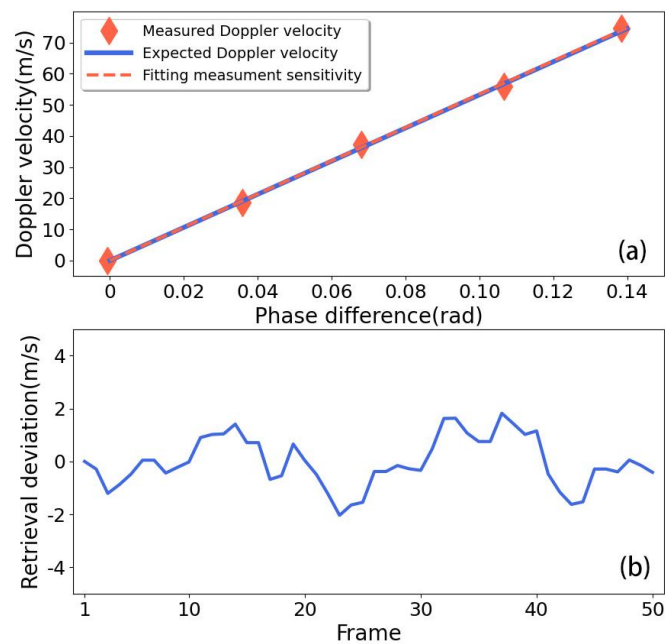


Fig. 9(a) Fitting results of the Doppler velocity compared with expectations. Each point is an average of 10 measurements. **(b)** Retrieval deviation of the retrieved Doppler velocity and the expectations.

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Fig. 9(a) shows the wind retrieval using the laboratory measurements mentioned before. The fitting coefficient is $532.2 \text{ ms}^{-1}/\text{rad}$, which is very close to the designed value $531.9 \text{ ms}^{-1}/\text{rad}$. The retrieval deviation from generated Doppler speed is shown in Fig. 9(b). In 50 samples, the deviation is distributed from -2 m/s to 1.8 m/s . Due to the lack of calibration line in this
310 experiment, an algorithm is applied to fit the thermal drift estimation curve by continuous sampling and piecewise fitting. Therefore, the deviation may be primarily induced by the thermal drift. The standard deviation was 0.95 m/s , and no systematic error was found.

6. First Field observations

Neutral wind measurements were conducted at Mohe Station (53.5°N , 122.3°E) during
315 nighttime on January 14, 2024, when the solar zenith angle exceeds 100° . The exposure time for each sample is 5 minutes, and a complete scanning cycle, which includes measurements in the northward, eastward, zenith, southward, and westward directions, takes approximately 26 minutes. The darkfield is taken every night before observation by closing the entrance aperture of the detector. Fig. 10 is an example of a raw image containing information of atomic oxygen
320 green line and calibration line. There are notches marked by laser on the top of one grating, which is used for calibrating the thermal drift outside the interferometer (Marr et al., 2020). After removing the dark field and replacing the hot pixels and spikes, the image is binned 2×8 , 2 pixels in x direction and 8 pixels in y direction, resulting in a final resolution of 1024×256 elements. In order to avoid large distortions at the interferogram edges, only 800×150 elements
325 are used for retrieving wind.

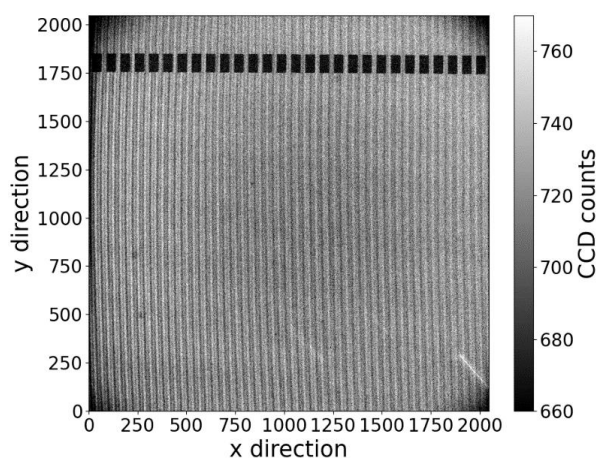


Fig. 10. Raw image, facing westward at a 45° elevation, captured at Mohe Station at 9:12 UT on January 14, 2024.

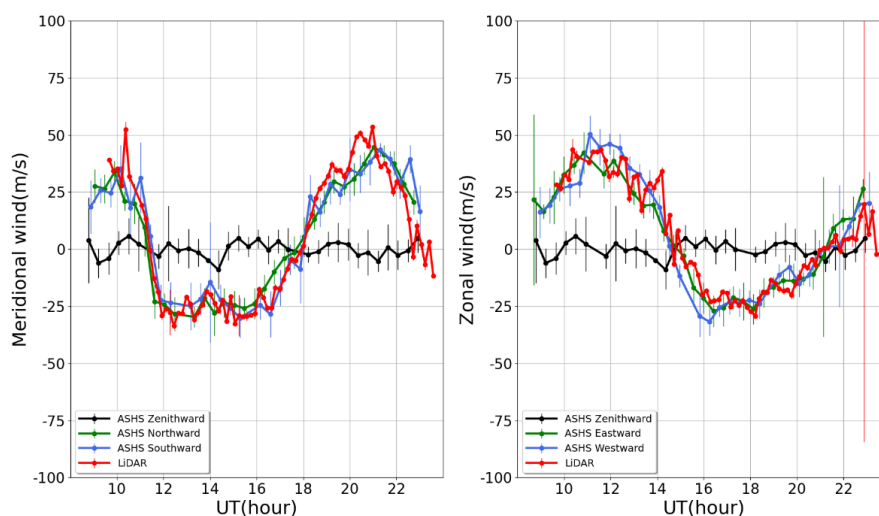


Fig.11. Neutral wind measured by the ASHS and the co-located LiDAR at Mohe Station during nighttime on January 14, 2024. The black, green and blue lines are obtained by the ASHS detecting in different directions. The red line represents the weighted average result of the LiDAR measurements at an altitude ranging from 90 to 100 km.

Fig. 11 shows the observational results of the geomagnetic quiet night on January 14, 2024 at Mohe station. After removing the outliers, the average phase in the zenith direction



throughout one night is taken as the zero-wind phase. In order to validate the ASHS instrument, the results are compared with measurements from atmosphere wind-temperature-metal-constituents LiDAR at Mohe station. The red line represents the weighted average result of LiDAR measurements at an altitude ranging from 90 to 100 km. The error bars represent a
340 combination of the uncertainty associated with the zero wind reference and the standard deviation between the fitted phase and the retrieved phase. This combination provides a comprehensive indication of the precision and reliability of the data.

During the observation periods, the sky was clear and geomagnetic activities were quiet. After sunset, the meridional wind was directed northward while the zonal wind blew eastward.
345 At about 11:30 UT, the meridional wind abruptly shifted to the southward direction and maintained a velocity of approximately 25 m/s until it steadily reverted to a northward direction from 18:00 UT to 20:00 UT. During the period from 14:00 UT to 16:00 UT, the zonal wind gradually transitioned from an eastward to a westward direction, subsequently reversing back to an eastward flow for the remainder of the observational period.

350 The meridional and zonal wind measurements from the ASHS and the LiDAR exhibit a satisfactory consistency in terms of both the temporal synchronization and the magnitude of wind variations. This congruency not only attests to the reliability of the ASHS in capturing wind dynamics but also underscores the comparability of the two distinct measurement systems. Additionally, the consistency of the east-west zonal wind and north-south meridional wind is
355 confirmed by the measurements, as the ASHS instrument's observations in opposite directions corroborate each other. Furthermore, the measured zenith wind remained close to zero throughout the night, indicating strong instrument stability.

To facilitate a comparative analysis of the correlation between data obtained from two distinct systems, it is imperative to standardize the observational outcomes. For this purpose,
360 data from both ASHS and LiDAR systems, collected during overlapping observation periods



spanning five days in January 2024, were utilized. Given the disparate observation frequencies of these systems, piecewise linear interpolation was employed to synchronize their time series. Subsequently, the average horizontal wind component aligned with the north-south axis was designated as the meridional wind, while that aligned with the east-west axis was identified as the zonal wind. The processed time series results, with a five-minute interval, are presented in Fig. 12. The upper and lower panels of the figure illustrate the meridional and zonal wind results, respectively. Within the figure, black dots signify LiDAR observations, whereas red dots represent observations from the ASHS interferometer. Notably, the observational data from both instruments exhibited good agreement on the nights of the 14th and 15th. However, from the 17th to the 31st, a certain degree of deviation was observed, which may primarily be attributed to inaccuracies in the weighted average calculation of LiDAR detection results across various altitudes. The spatial and temporal variability in the height distribution of oxygen atom OI 557.7 nm airglow necessitates a more precise weighted average computation, based on the specific airglow emissivity height distribution prevalent in the region on the respective day.

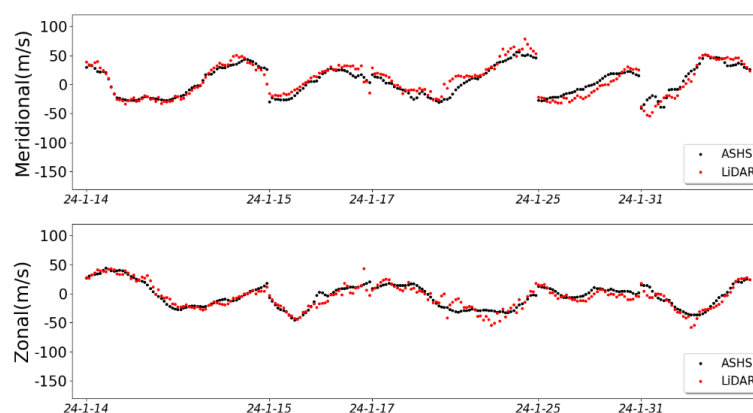
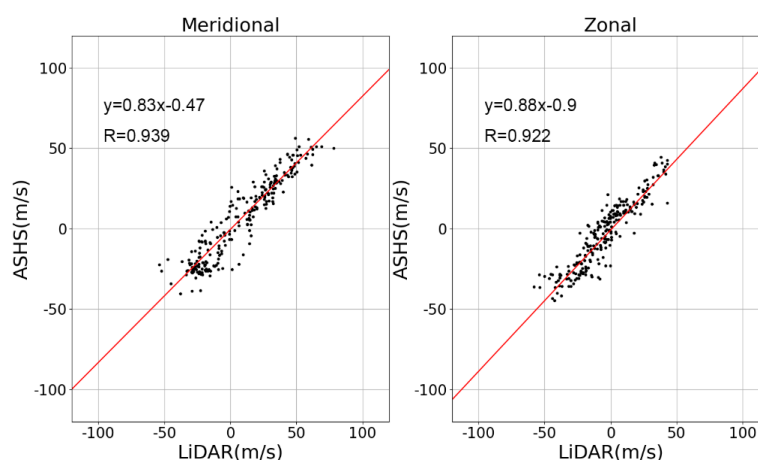


Fig.12. The top panel depicts the meridional wind component, while the bottom panel displays the zonal wind component. The black dots indicate observations recorded by the ASHS, and the red dots represent the weighted average results obtained from LiDAR observations.



380 **Fig.13. Correlation scatter plots of the comparison of neutral wind measured by the ASHS and LiDAR during nighttime in January 2024. The upper left corner indicates the linear fitting equation (y) and the Pearson correlation coefficient (R).**

Fig. 13 demonstrates the correlation between the observational outcomes of the ASHS interferometer and LiDAR. The vertical coordinates of the black dots in the figure represent the observational data from the ASHS interferometer, while the horizontal coordinates correspond to the weighted average of the measurement results obtained from LiDAR. The red line depicted in the figure results from a linear regression fit utilizing the least squares method. The upper left corner of the figure indicates the linear fitting equation (y) with regression slopes ($k = 0.83 \pm 0.03$ meridional; $k = 0.88 \pm 0.03$ zonal) and the Pearson correlation coefficient ($R = 0.939$ meridional; $R = 0.922$ zonal), both of which highlight a significant positive correlation between the observational results of the two systems. In the linear fitting equation for zonal wind, the slope is observed to be less than 1, which may be attributed to potential system biases between the two systems or errors introduced during the weighted averaging of wind measurement results from various altitudes recorded by LiDAR.

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395 7. Summary

We present a newly developed ground-based ASHS instrument for observing the atomic oxygen green line to derive neutral winds in mesopause region. The temperature of the interference module in the field observatory is kept within ± 0.1 °C of the target temperature by utilizing a combination of active and passive temperature control systems. The thermal compensation
400 design results in a spatial frequency thermal sensitivity of $0.038 \text{ cm}^{-1}/^{\circ}\text{C}$ and a phase offset thermal sensitivity of $0.624 \text{ rad}/^{\circ}\text{C}$. In laboratory measurements, the sensitivity of the DASH instrument on Doppler velocity is calibrated, indicating an uncertainty of less than 2 m/s due to the thermal sensitivity of the instrument. First field measurements taken at Mohe Station were presented, showing a well consistent picture of wind fields with the LiDAR measurements.

405 Data availability

The observational data of DCOI (Dual-Channel Optical Interferometer) and Na lidar in this paper are available at the Chinese Meridian Project (CMP) (<https://www.meridianproject.ac.cn>). The experimental data can be provided by the corresponding authors upon request.

Author contributions

410 YZ conceived and led the development; GZ assembled the instrument and wrote the manuscript draft; TW, WL and WY performed the measurements; SL and GY provided LiDAR data; MK and JX reviewed and edited the manuscript.

Competing interests

The authors declare no conflict of interest.

415 Acknowledgments

We thank the Chinese Meridian Project for the support fund. We are also grateful to the anonymous reviewers for their constructive comments and suggestions to improve this manuscript.



Financial support

- 420 This work was supported by the Project of Stable Support for Youth Team in Basic Research
Field, CAS (YSBR-018); the National Natural Science Foundation of China (42174212); the
Chinese Meridian Project; the Specialized Research Fund for State Key Laboratories.

References

- 425 Christensen, A. B., Spann, J., & Cyr, O. C. (2009). Heliophysics: The Solar and Space Physics of a New Era.
Recommended Roadmap for Science and Technology 2009-2030. NASA Advisory Council PB2010-100211.
- Dhadly, M., Sassi, F., Emmert, J., Drob, D., Conde, M., Wu, Q., Makela, J., Budzien, S., & Nicholas, A. (2023).
Neutral winds from mesosphere to thermosphere—past, present, and future outlook. *Frontiers in Astronomy and
Space Sciences*, 9, 1050586. <https://doi.org/10.3389/fspas.2022.1050586>
- 430 Dötzer, F. (2019). Calibration of a Doppler Asymmetric Spatial Heterodyne Interferometer for Atmospheric Wind
Measurements [Master's thesis]. Friedrich-Alexander-Universität Erlangen-Nuernberg.
- Englert, C. R., Babcock, D. D., & Harlander, J. M. (2007). Doppler asymmetric spatial heterodyne spectroscopy
(DASH): concept and experimental demonstration. *Applied Optics*, 46(29), 7297-7307.
- Englert, C. R., Harlander, J. M., Emmert, J. T., et al. (2010). Initial ground-based thermospheric wind measurements
435 using Doppler asymmetric spatial heterodyne spectroscopy (DASH). *Optics Express*, 18(26), 27416-27430.
- Englert, C. R., Harlander, J. M., & Brown, C. M. (2017). Michelson Interferometer for Global High-Resolution
Thermospheric Imaging (MIGHTI): Instrument Design and Calibration. *Space Science Reviews*, 212, 553-584.
- Harlander, J. M. (1991). Spatial heterodyne spectroscopy: Interferometric performance at any wavelength without
scanning [Ph.D. thesis].
- 440 Harlander, J. M., Englert, C. R., Babcock, D. D., & Roesler, F. L. (2010). Design and laboratory tests of a doppler
asymmetric spatial heterodyne (DASH) interferometer for upper atmospheric wind and temperature observations.
Optics Express, 18(25), 26430–26440.
- Hays, P. B., Killeen, T. L., & Kennedy, B. C. (1981). The Fabry-Perot Interferometer on Dynamics Explorer. *Space
Science Instrumentation*, 5, 395-416.
- 445 Hedin, A. E., Fleming, E. L., & Manson, A. H. (1989). Empirical wind model for the upper, middle and lower
atmosphere. *Journal of Atmospheric and Terrestrial Physics*, 58(13), 1421-1447.



- Gault, W. A., et al. (1996). ERWIN: an E-region wind interferometer. *Applied Optics*, 36(16), 2913-2922.
- Kelley, M. C.: The Earth's ionosphere Plasma Physics and Electrodynamics, Elsevier, 2009.
- 450 Killen, T. L., Wu, Q., & Solomon, S. C. (2006). TIMED Doppler interferometer: overview and recent results. *Journal of Geophysical Research*, 111, A10S01.
- Kristoffersen, S. K., Ward, W. E., Brown, S., et al. (2013). Calibration and validation of the advanced E-Region Wind Interferometer. *Atmospheric Measurement Techniques*, 6(7).
- Liu, J., Wei, D., Zhu, Y., Kaufmann, M., Olschewski, F., Mantel, K., Xu, J., & Riese, M. (2018). Effective wind and temperature retrieval from doppler asymmetric spatial heterodyne spectrometer interferograms. *Applied Optics*, 57(30), 8829-8835.
- 455 Marr, K. D., Thayer, A. S., Englert, C. R., & Harlander, J. M. (2020). Determining the thermomechanical image shift for the mIGHT instrument on the nasa-ICON satellite. *Optical Engineering*, 59(1), 1.
- McLandress, C., Shepherd, G. G., & Solheim, B. H. (1996). Combined mesosphere/thermosphere winds using WINDII and HRDI data from the Upper Atmosphere Research Satellite. *Journal of Geophysical Research*, 101(D6), 10441-10453.
- 460 Wei, D., Zhu, Y., Liu, J., et al. (2020). Thermally stable monolithic Doppler asymmetric spatial heterodyne interferometer: optical design and laboratory performance. *Optics Express*, 28(14).
- Wei, D. (2021). Development of an optical instrument for the observation of neutral winds in earth's upper atmosphere [Ph.D. thesis]. Universität Wuppertal, Fakultät für Mathematik und Naturwissenschaften.
- 465 Wei, D., Gong, Q., Chen, Q., Zhu, Y., Kaufmann, M., Olschewski, F., Knieling, P., Dötzer, F., Mantel, K., Xu, J., Koppmann, R., & Riese, M. (2022). Modeling and correction of fringe patterns in Doppler asymmetric spatial heterodyne interferometry. *Applied Optics*, 61, 10528-10537.
- Wu, Q., Gablehouse, R. D., Solomon, S. C., et al. (2004). A new Fabry-Perot interferometer for upper atmosphere research. In *Proceedings of SPIE - The International Society for Optical Engineering* (Vol. 5660, pp. 218-227).
- 470 Zhang, S. P., & Shepherd, G. G. (2005). On the response of the O(1S) dayglow emission rate to the Sun's energy input: An empirical model deduced from WINDII/UARS global measurements. *Journal of Geophysical Research Atmospheres*, 110(A3).
- Zhu, G., Zhu, Y., Kaufmann, M., Wang, T., Liu, W., & Xu, J. (2023). An Efficient Calibration System of Optical Interferometer for Measuring Middle and Upper Atmospheric Wind. *Remote Sensing*, 15, 1898.

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