



Simulation of a spaceborne metastable helium lidar

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Abstract. Metastable helium (He^{*}) lidar has extended atmospheric profiling into the thermosphere and lower exosphere in recent years. However, ground-based observations remain limited by weather conditions and geographic coverage. In this study, we propose a spaceborne He^{*} lidar concept and assess its performance through numerical simulations. We use a global He^{*} density model, compare its predictions with a representative ground-based observation, and specify the key instrument parameters. We then calculate the expected photon returns for an upward-looking lidar orbiting at approximately 400 km, accounting for saturation and measurement noise. Under the simulated conditions, He^{*} density profiles can be retrieved up to 1000 km with a vertical resolution of 5 km and an integration time of 1 min. We also investigate temperature and line-of-sight velocity retrieval using three probing wavelengths with retrievals reported at 20 km altitude intervals between 500 and 700 km. The temperature retrieval captures the main features of the prescribed profile. These results highlight the potential of spaceborne He^{*} lidar to extend localized ground-based observations towards global, altitude-resolved mapping of He^{*}. Beyond density profiling, future temperature and line-of-sight velocity measurements could provide new observational constraints on the thermal structure and dynamics of the upper thermosphere, supporting investigations of helium variability and the evaluation of thermospheric models.

1 Introduction

The upper thermosphere and lower exosphere respond to solar energy input and interactions between the neutral atmosphere and plasma. Measurements in this region are needed to determine how neutral constituents vary with solar and geomagnetic conditions. Neutral mass density also governs atmospheric drag on low-Earth-orbit spacecraft and is therefore relevant to orbit prediction (Siemes et al., 2016). Beyond measurements at a single altitude, vertically resolved observations are needed to characterize the altitude-dependent distribution of individual neutral constituents. Profiles are needed to distinguish changes



20 in abundance from changes in layer height or thickness. Recent He* observations have resolved such structures into the lower exosphere (Geach and Kaifler, 2025; Zhao et al., 2024), but their geographic coverage remains limited.

Satellite instruments measure different properties of the neutral atmosphere over different spatial scales (Siemes et al., 2016), for example, thermospheric mass density has been derived from Swarm non-gravitational accelerations using a model of the forces acting on the spacecraft. The resulting densities describe conditions along the orbit, without providing a simultaneous
25 vertical profile at each location. Passive limb sounding adds height-dependent information. The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) was designed to measure winds and temperatures between 90 and 300 km using oxygen emissions (Englert et al., 2017). Neither approach directly provides profiles of individual neutral constituents across the 400 to 1000 km region considered in this study. Species-selective lidar measurements could complement these observations by resolving distance along the viewing direction.

30 He* can be probed through its resonance transition near 1083 nm. Absorption excites atoms from the 2^3S state to the 2^3P manifold, and the subsequent fluorescence can be detected remotely (Kaifler et al., 2022; Zhao et al., 2024). The metastable population depends on electron-impact excitation of ground-state helium, recombination involving He⁺, and competing losses. The balance between these processes changes with the neutral and plasma environment. Recombination can contribute to the nighttime population and complicate the interpretation of the helium spectrum (Waldrop et al., 2005). He* observations thus
35 constrain this particular atomic population; inferring total helium abundance or neutral mass density requires a population model and additional atmospheric information. The fluorescence signal amplitude provides information on He* number density, while Doppler broadening and shift are sensitive to temperature and line-of-sight velocity, respectively. Their interpretation as bulk neutral temperature and wind depends on whether He* is in thermal and dynamical equilibrium with the surrounding neutral atmosphere.

40 Passive measurements of 1083 nm airglow predate He* lidar. Combined with modeling, spectroscopy of this emission has been used to study He* production and its dependence on the ionospheric environment (Waldrop et al., 2005). The observed brightness integrates emission along the viewing path, and its solar-resonance component depends on illumination of the He* layer. Hui et al. (2026) reported eight months of He* and oxygen airglow measurements from SPHEREx. Upward-looking observations from approximately 680 km revealed geographic and seasonal variations in the emission. These measurements
45 demonstrate orbital sampling of 1083 nm emission over a wide area. Lidar would add distance information to this sampling, allowing the vertical distribution to be resolved rather than inferred from integrated brightness alone.

Ground-based lidar has already measured He* density well into the upper thermosphere. Kaifler et al. (2022) reported profiles reaching 700 km. Using high-energy 1083 nm pulses, a telescope array, and a superconducting nanowire single-photon detector, Zhao et al. (2024) extended density measurements to 1000 km. Geach and Kaifler (2025) subsequently analyzed 51
50 measurements from the winter of 2023 to 2024, documenting altitude-dependent changes in a layer extending to 1000 km. Spectral measurements have also been demonstrated. By sampling the He* line at four wavelengths, Kaifler and Geach (2024) obtained a spectrum at 600 km and placed coarse constraints on temperature and vertical wind. Resolving the spectrum requires more photons than measuring its amplitude at one wavelength. These experiments establish the measurement principles needed to assess both density profiling and spectral sounding from orbit.



55 A spaceborne instrument would change both the sampling and the signal budget. Ground-based measurements depend on weather and optical background at individual stations. An upward-looking lidar within the lower part of the target region could observe the overlying He* population over a shorter path that avoids the lower atmosphere. Successive profiles along the orbit could span a wider range of latitudes, although the orbit would still determine local-time coverage. CALIOP cloud and aerosol profiling (Winker et al., 2007) and ALADIN wind measurements (Witschas et al., 2020) have demonstrated atmospheric lidar operation from space. Transmitter development for proposed space-based sodium resonance lidar is also relevant to an orbital He* instrument (Yu et al., 2016). The expected He* signal and its uncertainty nevertheless require a separate calculation because the target population, resonant response, and geometry differ from those of these systems.

Calculations for ground-based He* lidar illustrate the dependence of performance on atmospheric conditions (Lan et al., 2024), estimated density-measurement errors for a pulsed He* lidar under contrasting seasonal conditions. A laboratory instrument has also been developed to investigate the He* spectra (Wang et al., 2026b). For a spaceborne lidar, reducing the target distance increases the collected fluorescence, but it also raises the incident photon flux at fixed pulse energy and beam divergence. Near the platform, saturation can therefore limit the gain expected from inverse-square range scaling. At greater distances, the weaker returns must be distinguished from optical background and detector counts. The effective cross-section and receiver throughput determine the signal strength, while range-bin width and accumulation time set the number of photons available for each density estimate. Retrieving temperature and velocity adds the need to distinguish spectral broadening from a Doppler shift using a finite number of photons. Ratios between wavelength channels can cancel a common density-dependent amplitude, provided that channel responses and saturation are treated consistently. A performance calculation must account for these effects through both signal generation and retrieval.

In this study, we simulate a spaceborne He* lidar for density profiling and three-wavelength retrieval of temperature and line-of-sight velocity. We use a global He* density model with a representative orbital geometry and transmitter and receiver parameters to calculate saturation-corrected signals and generate photon-counting observations. A comparison with a Hainan lidar profile checks the density range adopted in the simulations. We then retrieve density and estimate its counting-noise uncertainty, followed by Monte Carlo temperature and velocity retrieval from the wavelength-dependent signal ratios. The profiles are interpreted at the different spatial averaging scales required by the two measurement modes. The calculations assess what the assumed photon budget can support and how the physical and retrieval assumptions limit that assessment. The following sections present the observation and spectral response models, the density environment and instrument configuration, and the density, temperature, and velocity simulations.

2 Observation Concept

2.1 Spaceborne Observation Concept

85 The proposed observation concept is a spaceborne He* resonance fluorescence lidar operating at 1083 nm. The instrument transmits pulsed laser radiation toward the atmosphere and detects laser-induced resonance fluorescence from He* along the line of sight. Photon arrival times provide range resolution, and the range bins are mapped to altitude using the satellite position



and viewing geometry. In this way, the measurement yields altitude-resolved He* density profiles along the satellite track. The basic observation geometry considered in this study is illustrated in Figure 1. The baseline altitude range and observing configuration, while the choice of local-time sampling is constrained by both the He* density distribution and the optical background. Before specifying the baseline orbital scenario, we therefore first examine the modeled He* density environment, including its local-time and seasonal variability. These environmental characteristics are then used to justify the favorable observing conditions used in the subsequent spaceborne lidar feasibility simulation.

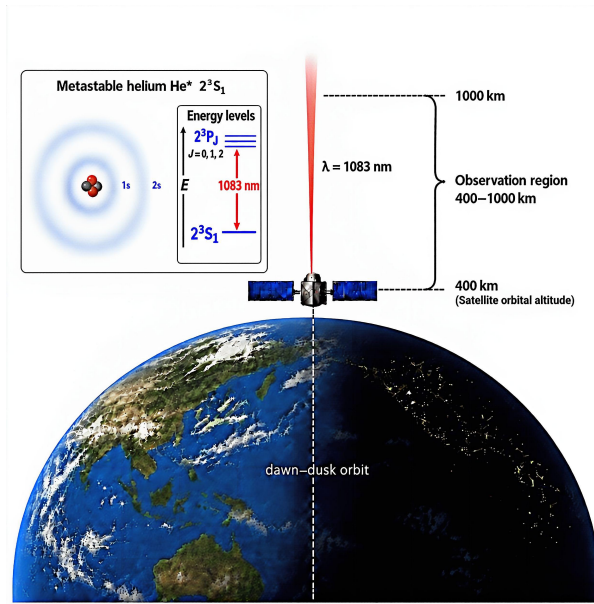


Figure 1. Conceptual illustration of the proposed spaceborne He* resonance fluorescence lidar. The satellite operates at an altitude of approximately 400 km and transmits 1083 nm laser pulses toward the thermosphere and lower exosphere. The target observation region extends from 400 km to 1000 km, where He* is detected through laser-induced resonance fluorescence. The dawn–dusk orbit shown here represents the baseline observing scenario evaluated in this study.

2.2 Lidar Concept

95 2.2.1 Lidar Equation

The lidar equation provides the basis for retrieving atmospheric information from the detected fluorescence signal. For the spaceborne He* lidar considered here, the expected number of detected signal photons from a given altitude bin can be expressed as Eq. (1):

$$N_{\text{sig}}(z) = \left[\frac{P_L \tau}{hc/\lambda} \right] \cdot [\sigma_{\text{eff}} \rho(z) \Delta z] \cdot \left[\frac{A_R}{4\pi(z - z_s)^2} \right] \cdot [\eta_1 \eta_2 T_a^2 E^2(z) G] \quad (1)$$



100 where $N_{\text{sig}}(z)$ represents the signal photon counts measured by the detector in the range interval $(z - \Delta z/2, z + \Delta z/2)$; z is the height of the detected target; z_s is the satellite orbital altitude; P_L is the laser power; h is the Planck constant; c is the speed of light; λ is the wavelength of the laser; σ_{eff} represents the effective scatter cross-section; $\rho(z)$ is the number density of He^* atoms; A_R is the area of the receiving telescope; $E(z)$ is the one-way extinction coefficient due to the absorption of the He^* layer, which is also approximately 1 because the number density of He^* is very low; The background photon counts are

$$105 \quad N_{\text{bg}}(z) = \frac{2(N_{\text{det}} + N_A)\tau\Delta z f}{c} \quad (2)$$

2.2.2 The Effective Scattering Cross-section

The effective scattering cross-section σ_{eff} is calculated by convolving the laser with the Doppler-broadened absorption profiles of the three fine-structure components of the 1083 nm transition, accounting for the finite laser linewidth and the Doppler shift due to relative motion along the laser line of sight. Assuming Gaussian profiles for both the laser spectrum and the individual
110 absorption lines, σ_{eff} can be expressed as:

$$\sigma_{\text{eff}} = \sum_{i=1}^3 w_i \frac{\sigma_{D_i} \sigma_0}{\sqrt{\sigma_{D_i}^2 + \sigma_L^2}} \exp \left\{ - \frac{[f_i - f_L(1 - v/c)]^2}{2(\sigma_{D_i}^2 + \sigma_L^2)} \right\}, \quad (3)$$

where w_i is the weighting factor for the i th spectral line; $\sigma_{D_i} = \sqrt{\frac{k_B T f_i^2}{m c^2}}$ is the rms linewidth due to Doppler broadening, with the speed of light c , the mass of a He^* atom m , the Boltzmann constant k_B , and temperature T ; $\sigma_0 = \frac{A_i c^2}{8\sqrt{2}\pi^{3/2} f_i^2 \sigma_{D_i}}$ is the peak absorption cross-section, where A_i is the spontaneous emission rate; σ_L is the rms width of the laser; $f_i = c/\lambda_i$ is the
115 resonance frequency of the transition; $f_L = c/\lambda_L$ is the laser frequency; v is the wind speed.

Using the above Eqs. 1-3, the density of He^* can be inferred from the known laser wavelength, power, and other system parameters. In contrast, retrieving temperature and wind speed requires measurements at multiple, carefully chosen wavelengths. Figure 2 illustrates the wavelength dependence of the σ_{eff} for the D_1 and D_2 transitions under different temperatures and wind speeds. The parameters used in these simulations are summarized in Table 1. As shown in Figure 2, increasing temperature
120 reduces the peak scattering cross-section and broadens the spectral lines, while changes in wind speed induce a Doppler shift. To simultaneously retrieve all three parameters, density, temperature, and wind velocity, at least three returned signal intensities at distinct wavelengths are needed; hence, the laser must support three-frequency switching. The gray lines (1083.318 nm, 1083.329 nm, and 1083.337 nm) in Figure 2 are provided merely as illustrative examples.

2.2.3 Saturation Effect

125 For the case that laser pulse duration is in the nanosecond range, Eq. 1 does not always hold the truth as the radiative lifetime of the atomic excited state is generally on the order of tens of nanoseconds. The finite lifetime of the atomic excited state will cause a saturation effect of the atomic layers. According to Eq. 1, the number of backscattered photons should be proportional to the flux of the transmitted laser photons. However, for large laser intensities, the returned fluorescence photons are no longer



Table 1. Simulation parameters for the effective scattering cross section of metastable helium.

Parameter and Symbol	Value
Temperature (T)	1000, 1500, 2000 K
Line-of-sight velocity (v)	-500, 0, 500 m/s
Laser frequency (f_L)	c/λ_L
Laser RMS linewidth (σ_L)	100 MHz
Relative line weights (w_i)	(1, 3, 5)/3
Spontaneous emission coefficient (A_i)	$1.0216 \times 10^7 \text{ s}^{-1}$
Helium atomic mass (m)	$6.64431932 \times 10^{-27} \text{ kg}$
Boltzmann constant (k_B)	$1.380649 \times 10^{-23} \text{ J K}^{-1}$
Speed of light (c)	299792458 m/s

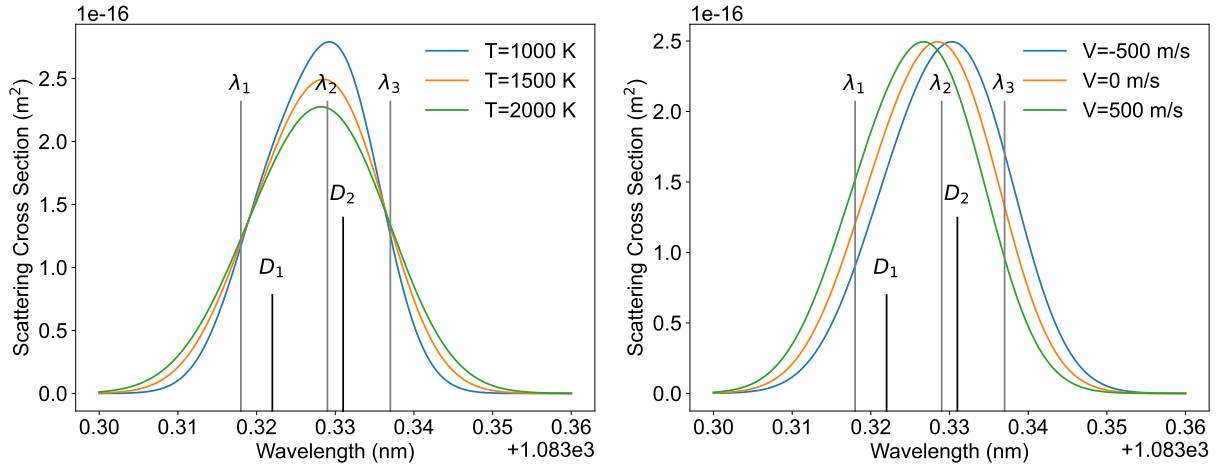


Figure 2. Simulated Doppler-broadened spectra of He* over a range of temperatures and wind speeds. The gray lines mark the measurement wavelengths, provided here merely as examples for illustration. The black vertical lines mark the two transitions D_1 and D_2 .

proportional to the laser power, but less than what is expected from Eq. 1. Saturation effect is defined as the deviation from this proportionality.

During the laser pulse duration Δt_L , the excited-state population n_e is not in the steady state, but is determined by the rate equation as below:

$$\frac{dn_e}{dt} = -\frac{n_e}{\tau_R} + (n - n_e) \frac{\sigma_{\text{eff}} N_L(t) T}{(z - z_s)^2 \Omega} - n_e \frac{\sigma_{\text{eff}} N_L(t) T}{(z - z_s)^2 \Omega} \quad (4)$$



where τ_R is the radiative lifetime of the excited state, n is the total number density of the atoms in the layer, i.e., the sum of the
 135 ground-state population ($n - n_e$) and the excited-state population n_e , $N_L(t)$ is the total number of laser-emitted photons per
 unit time, T is the one-way atmospheric transmission, and Ω is the solid angle illuminated by the laser beam. The solid angle
 Ω is related to the full divergence angle θ_L by $\Omega = \frac{\pi}{4}\theta_L^2$

In order to derive an analytical solution of Eq. 4, we assume that the temporal shape of the laser pulse can be represented by
 a rectangular shape with a width of Δt_L :

$$140 \quad N_L(t) = \begin{cases} \frac{N_L}{\Delta t_L}, & 0 < t < \Delta t_L, \\ 0, & t > \Delta t_L. \end{cases} \quad (5)$$

where N_L is the total number of emitted photons related to each pulse energy. By solving Eq.4, the excited-state population
 is given by

$$n_e(t) = \begin{cases} \frac{n\tau'}{2t_S} (1 - e^{-t/\tau'}), & t < \Delta t_L, \\ \frac{n\tau'}{2t_S} (1 - e^{-\Delta t_L/\tau'}) e^{-(t-\Delta t_L)/\tau_R}, & t > \Delta t_L. \end{cases} \quad (6)$$

where t_S and τ' are defined as $t_S = \frac{(z-z_s)^2 \Omega \Delta t_L}{2\sigma_{\text{eff}} N_L T}$, $\frac{1}{\tau'} = \frac{1}{\tau_R} + \frac{1}{t_S}$.

145 Since the decay rate of the excited-state population through spontaneous emission is $n_e(t)/\tau_R$, the number of reemitted
 photons per unit time in the volume considered will be $((z - z_s)^2 \Omega \Delta z) \frac{n_e(t)}{\tau_R}$. Its integration over time is the number of reemit-
 ted photons and can be used to replace the product of the first and second factors in Eq. 1. Therefore, the number of photons
 received by the lidar during the integration time will be given by Eq. 7:

$$N_{\text{sig,Sat}}(z) = N_{\text{sig}}(z) \frac{1}{1 + \frac{\tau_R}{t_S}} \left\{ 1 - \frac{\tau_R}{\Delta t_L} \frac{\frac{\tau_R}{t_S}}{1 + \frac{\tau_R}{t_S}} \times \left[\exp\left(-\frac{\Delta t_L}{\tau_R} \left(1 + \frac{\tau_R}{t_S}\right)\right) - 1 \right] \right\} \quad (7)$$

150 where $N_{\text{sig,Sat}}(z)$ is the signal photon number under saturation effects; τ_R is the radiative lifetime of the excited state (2^3P);
 t_S is defined as $t_S = \frac{(z-z_s)^2 \pi \theta^2 \Delta t_L}{8\sigma_{\text{eff}} N_L T_a}$; N_L is the total number of emitted laser photons per pulse.

The total photon counts at altitude (z) consist of the saturation-corrected He* fluorescence signal and the background con-
 tribution. Both terms are evaluated over the same accumulation period and altitude bin, yielding

$$N_{\text{tot}}(z) = N_{\text{sig,Sat}}(z) + N_{\text{bg}}(z) \quad (8)$$

155 Although the mean background can be subtracted to obtain the net fluorescence signal, its statistical fluctuations still contribute
 to the measurement uncertainty.

Assuming independent Poisson statistics for the signal and background photon counts, the photon-counting noise is charac-
 terized by the square root of the total expected counts. When the additional uncertainty associated with estimating the mean



background is negligible, the signal-to-noise ratio (SNR) at altitude (z) is given by Eq. (9):

$$160 \quad \text{SNR}(z) = \frac{N_{\text{sig,Sat}}(z)}{\sqrt{N_{\text{tot}}(z)}}. \quad (9)$$

This expression quantifies the detectability of the He^* fluorescence signal in the presence of photon-counting noise and provides a basis for evaluating the altitude-dependent measurement performance of the spaceborne lidar.

3 He^* Density Environment

3.1 Global He^* Density Model

165 The feasibility of a spaceborne He^* lidar depends directly on the expected spatial distribution of He^* . Here the atmospheric target field is provided by a global He^* model that couples the United States Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE-00), the Global Airglow (GLOW) model, and the International Reference Ionosphere (IRI) model (Picone et al., 2002; Solomon, 2017; Bilitza et al., 2017; Liu et al., 2026). The modeled density is obtained from the balance among source terms, chemical and radiative losses, and vertical diffusion. The primary production
 170 pathway is electron-impact excitation of ground-state helium by energetic electrons above the 19.8 eV threshold,



whereas electron recombination with He^+ provides an additional source, especially at night when direct photoelectron production is weakened (Noto et al., 1998; Waldrop et al., 2005; Kerr et al., 1996),



175 Energetic electron fluxes are calculated with GLOW. At middle and low magnetic latitudes, the calculation includes both local photoelectrons and conjugate photoelectrons transported along geomagnetic field lines. At high latitudes, auroral precipitation is treated as the dominant energetic electron source because conjugate photoelectron transport is limited. Loss terms include radiative decay, photoionization, and Penning ionization by N_2 , O_2 , and O (Bishop and Link, 1999). Neutral background parameters are taken from NRLMSISE-00, and the ionospheric electron and ion densities are obtained from IRI. The vertical
 180 diffusion equation is then solved with prescribed upper and lower boundary conditions. The solar and geomagnetic inputs, grid settings, boundary values, and numerical solution scheme follow the implementation described by Liu et al. (2026).

This coupled model is used to characterize the local-time, seasonal, and latitude-dependent variability of thermospheric He^* . These variations are important for the lidar design because the expected signal depends not only on the low absolute He^* density, which is generally below 1 cm^{-3} in the upper thermosphere and lower exosphere, but also on the optical background
 185 encountered along the orbit. Since He^* is the lower state of the 1083 nm resonance transition, even such tenuous populations can be probed through laser-induced resonance fluorescence under favorable illumination conditions (Kaifler et al., 2022; Zhao et al., 2024).

3.2 Local-Time and Seasonal Variations

The observing window of a He* resonance fluorescence lidar depends on both the He* density and the optical background, which vary with solar illumination. Figure 3 shows the modeled He* density over Hainan station (19.5°N, 109.1°E) throughout a full local-time cycle. The density variation reflects the changing balance between production and loss processes. However, a higher He* density does not necessarily imply more favorable observing conditions. Daytime illumination also introduces a strong solar-continuum background at 1083 nm, increasing photon-counting noise and potentially reducing the detection signal-to-noise ratio. Observations near the dawn and dusk terminators may therefore offer a favorable balance between He* abundance and optical background. This reasoning is consistent with previous studies identifying morning and evening twilight as favorable periods for observing the 1083 nm He* airglow (Waldrop et al., 2005). In particular, predawn conditions may favor lidar detection because of the reduced optical background, even when the He* density is below its daily maximum. These considerations motivate the adoption of a dawn–dusk orbital configuration in the baseline spaceborne lidar simulation.

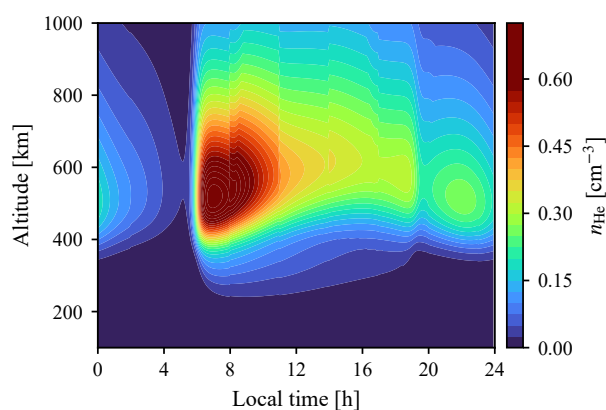


Figure 3. The He* density within one day at Hainan station, located at 19.5°N, 109.1°E. The height range is from 100 km to 1000 km.

Seasonal variability further changes the latitude range and altitude region that contribute most to the received lidar signal. Figure 4 presents four representative terminator cases on the equinox and solstice days. The modeled distribution shows a clear hemispheric asymmetry, with larger densities in the winter hemisphere and smaller densities in the summer hemisphere. This pattern is consistent with the winter helium bulge, which arises from seasonal changes in thermospheric composition and circulation (Keating and Prior, 1968). In addition to the large-scale seasonal structure, localized enhancements appear at high latitudes. These features are associated with auroral electron precipitation, represented in the model through the Zhang–Paxton parameterization (Zhang and Paxton, 2008). For the present feasibility study, these results indicate that a single fixed density profile is not sufficient for evaluating a spaceborne He* lidar. The end-to-end simulation must therefore consider representative density conditions rather than only an idealized maximum-signal case.

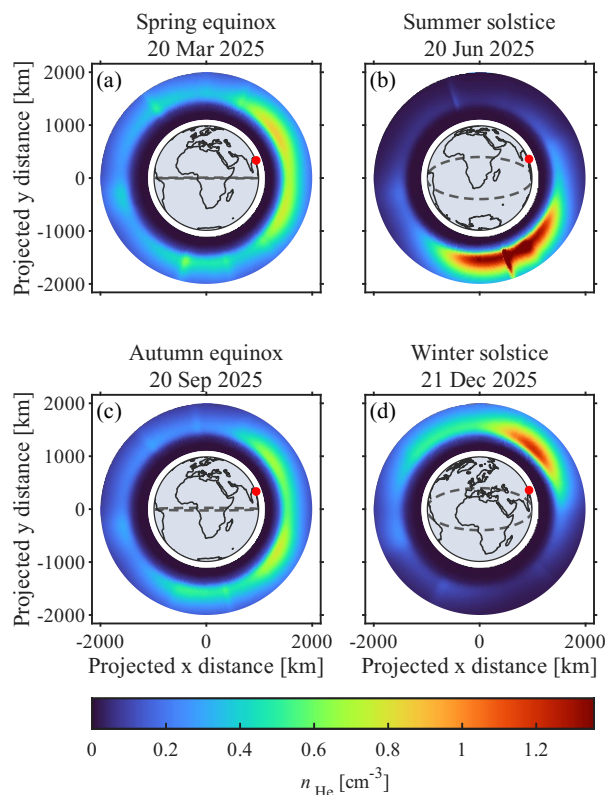


Figure 4. The He^* density over Hainan along the solar terminator on (a) spring equinox, (b) summer solstice, (c) autumn equinox, and (d) winter solstice. The red dot marks Hainan. The height range is from 100 km to 1000 km, and the Earth radius has been shrunk to 1000 km for better visualization.

3.3 Comparison With Ground-Based Lidar Observations

Before using the modeled density field in the spaceborne lidar calculation, we compare it with a representative ground-based He^* lidar observation. Figure 5 shows the modeled and observed profiles over Hainan at 2025-10-10 02:59:23, corresponding to an autumn-night case with moderate He^* density. The modeled profile captures the observed order of magnitude and the main altitude structure within the observational uncertainty. This comparison does not constitute a full validation of the global model, because it is based on a single station and a limited observing condition. However, it shows that the model provides a physically reasonable target-density range for estimating signal strength, retrieval uncertainty, and sensitivity to instrument parameters. The comparison is therefore used here as a consistency check before the model output is adopted in the following spaceborne lidar feasibility simulations.

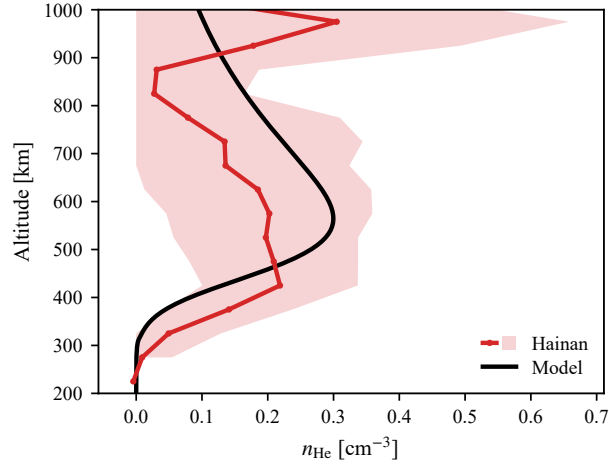


Figure 5. Comparison between the simulated He* density and the Hainan lidar observation at 2025-10-10 02:59:23. The black curve shows the simulated profile, the red curve shows the Hainan observation, and the shaded region denotes the observational uncertainty.

4 Spaceborne He* Lidar Configuration

4.1 Orbit and Observation Geometry

In the simulations, the satellite is assumed to operate in a dawn–dusk orbit at an altitude (z_s) of approximately 400 km. This orbital configuration is selected to take advantage of the relatively high He* density and reduced background illumination during twilight, providing favorable conditions for detecting weak He* fluorescence signals. The observation region of the spaceborne He* lidar is designed as 400 km to 1000 km, where the atmospheric density is extremely low, so the effects of atmospheric scattering and absorption are negligible. Then the atmospheric transmittance (T_a) is assumed to be 1, and the sky background noise is dominated by astronomical sources, instead of atmospheric scattering. The astronomical background at 1083 nm was estimated using the IRSA/IPAC Background Model (Wright, 1998). The total background component was evaluated on a $4^\circ \times 4^\circ$ J2000 RA–Dec grid with the observer location set to Earth (Figure 6).

The adopted background radiance is $L_{BG} = 5.29 \times 10^{-9} \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$. Substituting this value into Eq. (12) gives a corresponding astronomical background count rate of $N_A = 4 \text{ s}^{-1}$:

$$N_A = L_{BG} A_{tel} \Delta \lambda \pi \left(\frac{\theta_{FOV}}{2} \right)^2 T_r \frac{\lambda}{hc} \eta \quad (12)$$

Temperature and line-of-sight (LOS) wind profiles were prescribed to represent nonmonotonic variations within the 500–700 km altitude range. The temperature profile exhibited a pronounced maximum and a shallower minimum, while the LOS wind increased to a maximum before decreasing with altitude. These idealized profiles were selected to assess the ability of the retrieval method to resolve nonmonotonic vertical structures, with the prescribed wind speeds representing magnitudes

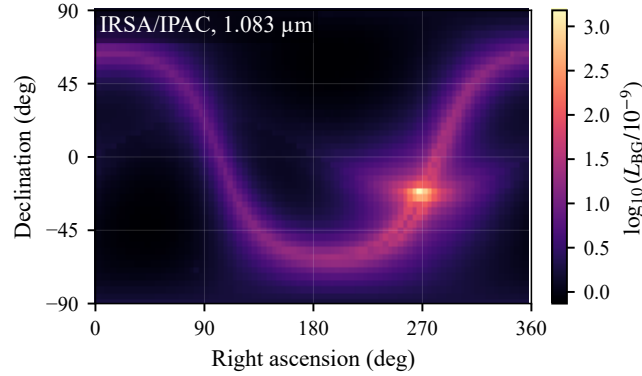


Figure 6. Astronomical background radiance at 1083 nm estimated from the IRSA/IPAC Background Model. Grid points within 5° of the solar direction are excluded when selecting the representative background value.

of the order of 10^2 m/s relevant to thermospheric circulation. The prescribed profiles served as references for evaluating the
 235 temperature and wind retrievals (Zhou et al., 2026; Drob et al., 2015).

4.2 Spaceborne He* Lidar Configuration

Similar to the ground-based He* lidar system (Zhao et al., 2024; Zhou et al., 2026), the spaceborne He* lidar system consists of three main subsystems: a laser transmitting subsystem, a telescope subsystem, and a detecting subsystem. The laser transmitting subsystem emits 1083 nm laser pulses, which excite resonance fluorescence scattering in He*. The telescope subsystem collects
 240 the fluorescence signals. The detecting subsystem converts the received optical signal into an electrical signal.

4.2.1 Laser Transmitting Subsystem

The 1083 nm laser is generated using an all-solid-state optical parametric generator–optical parametric amplifier (OPG–OPA) system (Xiao et al., 2023; Wang et al., 2026a). It delivers a pulse energy (E_{Laser}) of 120 mJ at a repetition rate of 120 Hz, corresponding to an average output power of 14.4 W. The OPG–OPA configuration provides high-energy output in the vicinity of the He* 1083 nm triplet and supports wavelength tuning among the selected probing wavelengths. This combination
 245 of high pulse energy, rapid pulse accumulation, and wavelength tunability provides an adequate photon budget for resolving the extremely weak He* fluorescence returns under spaceborne observation conditions. Although the OPG–OPA architecture represents one of the most challenging technologies for a spaceborne He* lidar, high-energy OPA technology has been successfully demonstrated in CO₂ spaceborne lidar transmitters (Zhu et al., 2020), indicating a feasible pathway toward space
 250 qualification. Since the spaceborne lidar operates significantly closer to the signal region than ground-based systems, the laser divergence angle (θ) is set to 0.1 mrad to mitigate saturation effects.

A saturated absorption frequency stabilization technique can be employed to achieve a laser with frequency fluctuations of less than 3 MHz and a root-mean-square frequency fluctuations of 0.446 MHz, providing a stable reference for an optical



phase-locked loop to realize tunable multi-wavelength output. With this seed laser, He* lidars will not only enable accurate
255 density observations but also allow for more precise retrievals of temperature and wind speed. This approach also offers a
practical and robust seed laser solution for existing He* lidar systems.

4.2.2 Telescope Subsystem

The telescope diameter (D) is set to 1.5 m with reference to the aperture of the China Space Station Survey Telescope Gong
et al. (2026). For direct coupling into a multimode fiber, the effective focal length of the receiving telescope (f_T) must satisfy
260 both the fiber-core-size and numerical-aperture (NA) matching conditions. For a fiber with core diameter $d_f=400 \mu\text{m}$, the
corresponding full-angle field of view is approximately

$$\Theta_{\text{FOV}} \approx \frac{d_f}{f_T}. \quad (13)$$

An atmospheric return with a laser divergence angle (θ), therefore produces a geometric image diameter at the focal plane of
 $d_{\text{spot}} \approx f_T \theta$. (14)

265 Requiring this image to fit within the fiber core, i.e., $d_{\text{spot}} \leq d_f$, imposes an upper limit on the focal length.

Meanwhile, under an equivalent thin-lens approximation, the convergence half-angle of the focused beam must not exceed
the fiber acceptance half-angle. For coupling in air or vacuum, this condition is expressed as

$$\arctan\left(\frac{D}{2f_T}\right) \leq \arcsin(\text{NA}), \quad (15)$$

which imposes a lower limit on the focal length. Combining the core-size and NA constraints gives the allowable focal-length
270 range:

$$\frac{D}{2 \tan[\arcsin(\text{NA})]} \leq f_T \leq \frac{d_f}{\theta} \quad (16)$$

An effective focal length of $f_T = 3.5 \text{ m}$ is therefore adopted within this range. According to Eqs. (13) and (14), this con-
figuration provides an effective full-angle field of view of approximately 0.114 mrad and a geometric image diameter of
approximately 350 μm , comparable to the fiber-core diameter. The required numerical aperture is

$$275 \text{ NA}_{\text{req}} \approx \sin\left[\arctan\left(\frac{D}{2f_T}\right)\right] \approx 0.21 \quad (17)$$

which is below the fiber NA of 0.22. Thus, the selected telescope and fiber parameters satisfy both matching conditions under
the assumed geometric-optics approximation. An orbital period of 92 min at an altitude of 400 km implies a platform speed of
approximately 7.7 km s^{-1} . To maintain efficient fiber coupling, the relative pointing of the transmitting and receiving optics
can be pre-adjusted to compensate for calibrated alignment offsets, while retaining sufficient field-of-view margin for the finite
280 return-image size and residual pointing errors.



4.2.3 Detecting Subsystem

For the detection subsystem, an optical filter with a bandwidth ($\Delta\lambda$) of 0.1 nm is employed to suppress broadband solar and atmospheric background radiation while maintaining sufficient spectral transmission for the Doppler-broadened He* fluorescence signal. Single-photon detection technologies have already been successfully demonstrated in spaceborne lidar missions (Ren et al., 2017), indicating the technological maturity of photon-counting architectures for orbital remote-sensing applications. Accordingly, a superconducting nanowire single-photon detector (SNSPD) is adopted as the baseline detector because of its high detection efficiency at 1083 nm, ultra-low dark-count rate, low timing jitter, and excellent single-photon sensitivity. These characteristics are particularly beneficial for resolving the extremely weak He* fluorescence returns under a photon-starved detection regime and for improving the signal-to-noise ratio over long atmospheric paths. In addition, the mechanically stable optical configuration and relatively well-controlled coupling conditions of a spaceborne payload can facilitate efficient photon collection and stable fiber coupling to the SNSPD. Although cryogenic cooling and space qualification remain important engineering considerations, the combination of narrowband background suppression and high-performance photon-counting detection makes SNSPD a promising choice for future spaceborne He* lidar missions. Detailed parameter design of the spaceborne He* Lidar is shown in Table 2.

5 Comparison between prescribed and retrieved atmospheric parameters

5.1 Metastable helium density

The retrieval simulation was constructed using the fluorescence lidar equation (Eq. 1), in which the wavelength-dependent effective scattering cross-section was calculated according to Eq. 3, while the reduction in fluorescence efficiency caused by laser saturation was incorporated through the saturation correction factor defined in Eq. 7. The instrumental, orbital, atmospheric, and detection parameters listed in Table 2 were adopted to calculate the expected He* fluorescence signal and background photon counts at each altitude and wavelength channel. The simulated observations were then generated by drawing photon counts from Poisson distributions with means given by the corresponding signal-plus-background counts. During the inversion, the estimated mean background was subtracted from the observed photon counts to obtain the net He* fluorescence signal. The He* density was subsequently retrieved by inverting the fluorescence lidar equation using the prescribed system parameters, effective scattering cross-sections, and saturation correction factors.

$$\rho_{\text{ret}}(z) = \frac{N_{\text{obs}}(z) - \bar{N}_{\text{bg}}(z)}{K_{\text{sat}}(z)} \quad (18)$$

where $K_{\text{sat}}(z)$ is the saturation-corrected signal response per unit He* density, calculated from Eqs. 1 and 7, and the overbar denotes the expected count level. The 1σ uncertainty was estimated by propagating the Poisson counting noise,

$$\sigma_{\rho}(z) = \frac{\sqrt{\bar{N}_{\text{tot}}(z)}}{K_{\text{sat}}(z)} \quad (19)$$

Table 2. Spaceborne He* Lidar System Parameters

Category	Parameter and Symbol	Value
Satellite	Orbit altitude (z_s)	400 km
	Orbital period (T_o)	92 min
	Latitude resolution ($\Delta\varphi$)	3.8°
	Longitude resolution ($\Delta\lambda$)	0.7°
Atmosphere	Atmospheric transmittance (T_a)	1
	Astronomical background noise (N_A)	4 s ⁻¹
	He* temperature (T)	800 K
	Vertical wind speed (V)	0 m s ⁻¹
Lidar	Laser energy (E_{Laser})	120 mJ
	Pulse repetition frequency (f)	120 Hz
	Laser divergence angle (θ)	0.1 mrad
	Laser pulse duration (Δt_L)	10 ns
	Integration time (τ)	1 min
	Telescope diameter (D)	1.5 m
	focal length (f_T)	3.5 m
	fiber-core diameter (d_f)	400 μm
	Optical efficiency (η_1)	25%
	Vertical resolution (Δz)	5 km
	Filter bandwidth ($\Delta\lambda$)	0.1 nm
	Detector efficiency (η_2)	30%
	Detector noise (N_{det})	170 s ⁻¹
	Geometrical factor (G)	1

Figure 7 shows the density retrieval results and SNR of the spaceborne He* lidar at different heights. The results show that the spaceborne He* lidar can retrieve He* density with a SNR at least one order of magnitude higher than that of ground-based He* lidar observations (Kaifler et al., 2022; Zhao et al., 2024). The retrieved profile maintains useful detection capability up to 1000 km, suggesting potential detectability beyond 1000 km, where He* has not yet been detected. The SNR decrease near 400 km is caused by saturation effects, which become important close to the lidar platform.

5.2 Temperature and line-of-sight wind velocity

Synthetic photon-count observations containing Poisson counting noise were generated for temperature and line-of-sight wind retrievals. Prescribed temperature and wind profiles, together with the modelled metastable helium density profile, were used to

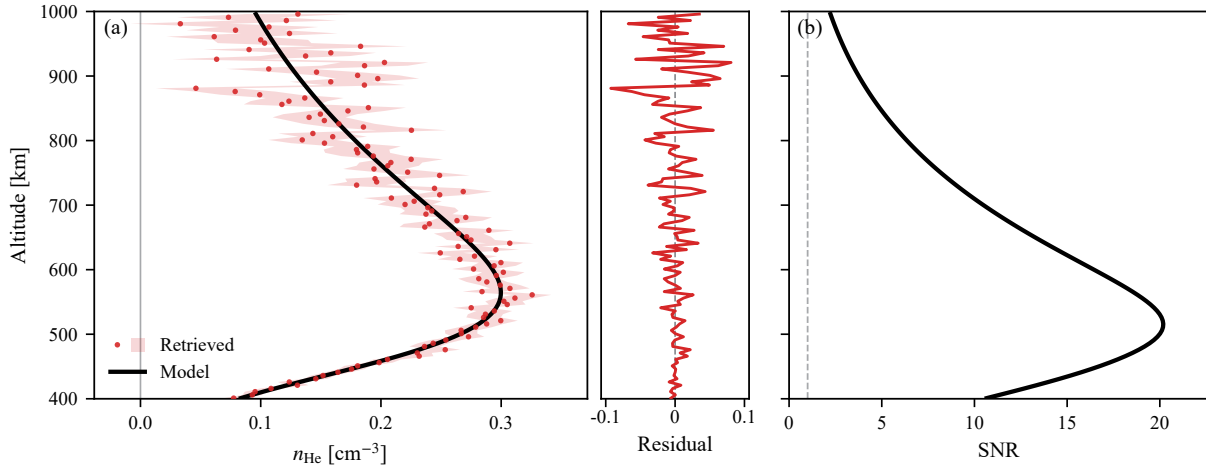


Figure 7. Density retrieval results and SNR of the spaceborne He* lidar at different heights. (a) Retrieved He* density compared with the model profile; the shaded region denotes the 1σ retrieval uncertainty, and the side axis shows the residual, defined as $\rho_{\text{ret}}(z) - \rho(z)$. (b) Simulated SNR profile; the dashed vertical lines mark SNR level of 1.

calculate the expected fluorescence signal at 1083.318, 1083.329 and 1083.337 nm through the forward lidar model, accounting for the temperature- and wind-dependent scattering cross sections, saturation correction and instrument parameters. For each raw altitude gate and wavelength, the observed photon count was sampled from a Poisson distribution with a mean equal to the sum of the expected signal, optical background and detector dark counts.

A single noisy total-count dataset $N^{(0)}$ was first generated from the forward model and held fixed. We then generated 1,000 conditional Poisson resamples using $N^{(0)}$ as the Poisson mean. Photon counts were accumulated within a 60 km sliding window, with successive window centers spaced at 20 km intervals. Specifically, for each realization $r = 1, \dots, N_{\text{MC}}$, conditionally independent Poisson counts given $N^{(0)}$ were drawn for every raw gate and wavelength:

$$N_{ij}^{(0)} \sim \text{Poisson}(S_{ij} + B_j), \quad (20)$$

$$N_{ij}^{(r)} | N^{(0)} \sim \text{Poisson}(N_{ij}^{(0)}). \quad (21)$$

where i indexes the raw range gates and j indexes the wavelength channels. Here, $N_{ij}^{(0)}$ denotes the fixed noisy total count generated once for gate i and channel j . $N_{ij}^{(r)}$ denotes the photon count in range gate i and wavelength channel j for the r th Monte Carlo realization, S_{ij} is the expected signal count, and B_j is the expected background count per range gate in wavelength channel j .



Counts were accumulated over nominal 60 km windows centred at $z_k = 500, 520, \dots, 700$ km. Let $W_{ki} = 1$ when $z_k - 30 \leq z_i < z_k + 30$ km and zero otherwise, and let $M_k = \sum_i W_{ki}$. Background-subtracted counts and their variances were

$$Y_{kj}^{(r)} = \sum_i W_{ki} N_{ij}^{(r)} - M_k B_j, \quad (22)$$

$$335 \quad V_{kj}^{(0)} \equiv \text{Var}\left(Y_{kj}^{(r)} \mid N^{(0)}\right) = \sum_i W_{ki} N_{ij}^{(0)} \quad (23)$$

where k indexes the accumulation windows, $Y_{kj}^{(r)}$ denotes the background-subtracted count in window k and wavelength channel j for realization r , and $V_{kj}^{(0)}$ is its variance. Only complete raw gates were accumulated. The effective widths at 500, 520, 680 and 700 km were 30, 50, 51 and 31 km, respectively; all other windows contained 60 gates. A single raw-count realization was shared by all windows in a trial. This preserves the covariance generated by overlapping windows.

340 At each altitude and for each MC realization, the observation vector was constructed using channel 2 as the reference:

$$\mathbf{q} = \begin{pmatrix} Y_1/Y_2 \\ Y_3/Y_2 \end{pmatrix}, \quad \mathbf{J} = \begin{pmatrix} 1/Y_2 & -Y_1/Y_2^2 & 0 \\ 0 & -Y_3/Y_2^2 & 1/Y_2 \end{pmatrix}. \quad (24)$$

where $\mathbf{J}$ is the Jacobian of $\mathbf{q}$ with respect to (Y_1, Y_2, Y_3) , and Σ_q is the first-order approximation to the covariance matrix of the two channel ratios. Its off-diagonal entries account for the correlation induced by the shared reference count Y_2 . The altitude and realization indices are omitted here for clarity. First-order propagation from independent channel counts gives:

$$345 \quad \Sigma_q^{(r)} = \mathbf{J}^{(r)} \text{diag}\left(V_1^{(0)}, V_2^{(0)}, V_3^{(0)}\right) \mathbf{J}^{(r)\top}. \quad (25)$$

The off-diagonal term accounts for the shared noisy denominator. The fixed count variances $V_j^{(0)}$ were obtained from the fixed observed total counts. The Jacobian $\mathbf{J}^{(r)}$, and hence $\Sigma_q^{(r)}$, was recalculated for each resample and held fixed during the corresponding optimization. For a single effective temperature T and wind v within a window, the predicted ratio vector was:

$$\mathbf{g}(T, v) = \begin{pmatrix} E_{\text{Laser}} f \tau \lambda_1 \sigma_1(T, v) / (E_{\text{Laser}} f \tau \lambda_2 \sigma_2(T, v)) \\ E_{\text{Laser}} f \tau \lambda_3 \sigma_3(T, v) / (E_{\text{Laser}} f \tau \lambda_2 \sigma_2(T, v)) \end{pmatrix} \quad (26)$$

350 Because the measurements at different wavelengths are closely spaced in time and made at long ranges, common density, geometrical and saturation factors cancel under this single-temperature, single-wind approximation. Channel-specific energy, pulse allocation and emitted-photon wavelength factors were retained. Density was therefore used to generate the signal and noise levels but was not supplied as a fitted parameter or direct input to the ratio inversion. The estimate was obtained by minimizing

$$355 \quad (\hat{T}, \hat{v}) = \arg \min_{(T, v) \in \mathcal{D}} [\mathbf{g}(T, v) - \mathbf{q}]^\top \Sigma_q^{-1} [\mathbf{g}(T, v) - \mathbf{q}], \quad (27)$$

$$\mathcal{D} = [200, 4000] \text{ K} \times [-2000, 2000] \text{ ms}^{-1}. \quad (28)$$



The objective was first evaluated on a grid with spacings of 10 K and 5 m/s. Its lowest grid value initialized a bounded continuous least-squares refinement. With $\Sigma_q = LL^T$, the optimizer minimized the squared norm of $L^{-1}(g - q)$. This coarse-grid initialization does not establish a global optimum for arbitrary observations. The bounds define the feasible search domain and are not a sampled prior.

Following the retrieval procedure described above, we generated 1,000 Poisson resamples from a single fixed photon-count dataset that already contained photon-counting noise, and retrieved temperature and line-of-sight wind from each resample. Figure 8 shows the frequency distributions of the retrieved temperature and wind, together with their smoothed joint distribution, illustrating the retrieval variability under Poisson resampling conditional on this fixed noisy observation. At each altitude, the final temperature and line-of-sight wind estimates were calculated as the arithmetic means of the corresponding retrieved values across the 1,000 realizations.

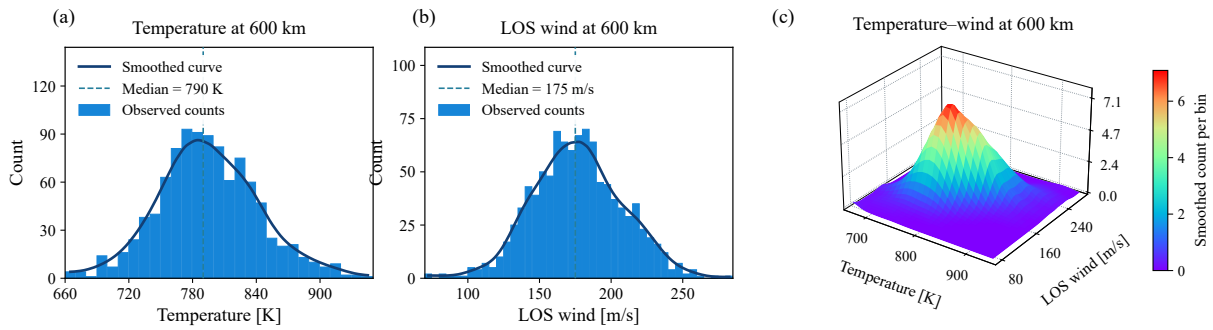


Figure 8. Frequency distributions of (a) temperature and (b) line-of-sight wind from conditionally independent Poisson resamples of one fixed noisy observation, with bin widths of 10 K and 5 m/s, respectively. Blue bars indicate counts, dark-blue curves show the smoothed distributions, and vertical dashed lines mark the medians. (c) Smoothed joint frequency distribution of temperature and line-of-sight wind. Surface height and colour indicate the smoothed count per two-dimensional bin, without probability normalization.

Figure 9 summarizes temperature and LOS wind retrievals from 1,000 Poisson resamples of the same fixed noisy photon-count dataset over 500–700 km. The red points represent the MC means, and the shaded bands show ± 1 sample standard deviation across retrievals. The retrieved temperature broadly follows the prescribed profile, with positive residuals around 520–580 km and the largest negative residual, approximately -68 K, at 640 km. The retrieved LOS wind is generally lower than the reference, with the largest negative residual of approximately -43 m/s also occurring at 640 km. At low signal-to-noise ratios, the retrievals are more sensitive to photon-counting fluctuations, which can produce substantial deviations from the reference profiles. Because the initial noisy dataset is fixed, these deviations are not necessarily removed by averaging the resampled retrievals. The standard deviations range from approximately 46 to 96 K for temperature and from 26 to 65 m/s for LOS wind, reaching their largest values at 700 km.

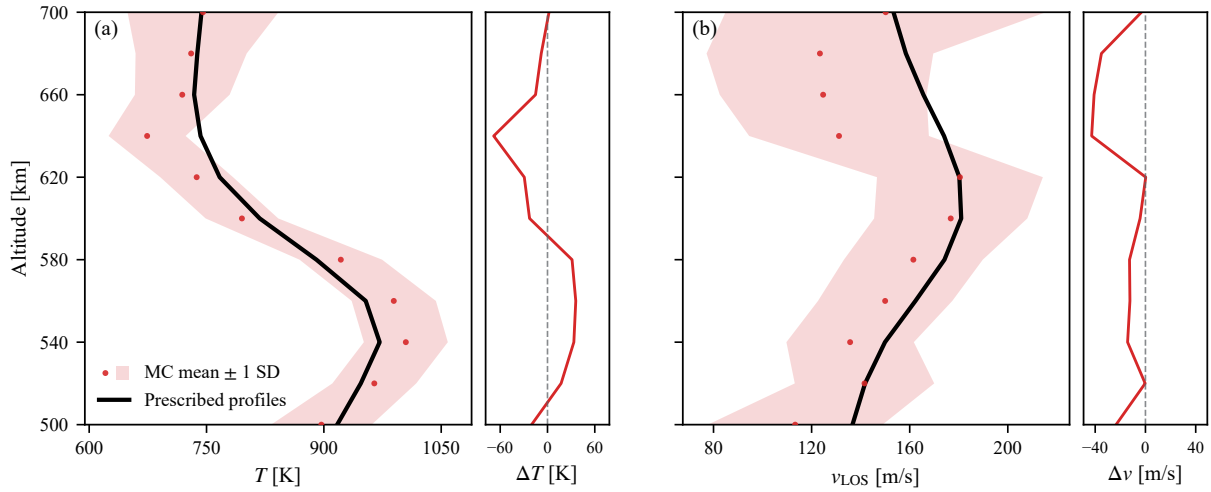


Figure 9. MC retrievals of temperature and line-of-sight wind from three-wavelength signal ratios. From left to right, the panels show temperature, temperature residuals, line-of-sight wind, and wind residuals. Black curves represent arithmetic window means of the prescribed profiles, red dots denote the mean retrieved values across 1,000 conditionally independent Poisson resamples of the same fixed noisy observation, and shaded bands indicate the MC means ± 1 sample standard deviation. Residuals are defined as the MC means minus the corresponding window-averaged reference values.

6 Conclusions

We evaluated a spaceborne He* lidar concept for profiling the thermosphere and lower exosphere through numerical simulations. For an upward-looking instrument orbiting at approximately 400 km, the simulations indicate the feasibility of retrieving He* density profiles up to 1000 km with a vertical resolution of 5 km and an integration time of 1 min under the assumed
 380 atmospheric and instrument conditions. Three-wavelength simulations also suggest the potential for joint temperature and line-of-sight velocity retrievals between 500 and 700 km, using 60 km accumulation windows sampled at 20 km altitude intervals. The conditional MC ensemble broadly reproduced the prescribed vertical structure, although residuals include contributions from photon-counting noise, vertical averaging, and the single-pair model approximation. These results support further investigation of spaceborne He* lidar as a complement to ground-based observations, with the potential to expand the geographic
 385 coverage of He* measurements and constrain upper-atmospheric thermal structure and dynamics. Future work should quantify ensemble retrieval accuracy and uncertainty calibration, assess instrumental systematic errors, and evaluate performance across a broader range of atmospheric and background conditions.

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390 Jinru Cheng, Tangsheng Cheng, Zhenwei Liu, Chen Liang, Tingdi Chen, Weilong Luo, and Chong Wang contributed to formal analysis and investigation.

Competing interests. The authors declare no conflicts of interest.

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