



Multiwavelength Emission Altitudes Constrain the Role of O₂ Dissociative Excitation in Auroral OI 844.6 nm Emission

Sota Nanjo¹, Tomoe Taki¹, Tima Sergienko¹, and Urban Brändström¹

¹Swedish Institute of Space Physics (IRF), Kiruna, Sweden

Correspondence: Sota Nanjo (sota.nanjo@irf.se)

Abstract. Multiwavelength imaging of auroral emissions is widely used to diagnose the characteristic energy of precipitating electrons, often through intensity ratios between prompt emission lines such as N₂⁺ 427.8 nm and OI 844.6 nm. The 844.6 nm emission can be produced by both direct excitation of atomic oxygen (O) and dissociative excitation of molecular oxygen (O₂), but their relative contributions cannot be separated from single-site, column-integrated intensity measurements alone. Here, we use emission altitude as an independent observational constraint on the 844.6 nm emission processes. We analyze diffuse aurora observed during one night with five ground-based stations in northern Sweden and continuously estimate the emission altitudes at 427.8 and 844.6 nm. During the 294 min for which emission altitudes were determined at both wavelengths, the two peak altitudes varied together, while the 844.6 nm emission peak was located above the 427.8 nm peak in 83% of the measurements, with a median altitude difference of 2.0 km. We then use the 427.8 nm peak altitude as an observational proxy for the penetration depth of the precipitating electrons and compare the observed relationship between the two peak altitudes with calculations by two different electron transport models. In calculations without O₂ dissociative excitation, the 844.6 nm peak altitude was increasingly overestimated toward lower 427.8 nm peak altitudes. Including O₂ dissociative excitation reduced the altitude discrepancy between the model and observations by approximately 70%. Despite their different electron-transport formulations, both models showed the same energy-dependent response: the downward shift of the 844.6 nm peak due to O₂ became apparent at a Maxwellian characteristic energy of approximately 5 keV and increased progressively with characteristic energy. Together, the observations and model comparisons provide the first altitude-based observational evidence for an O₂ dissociative-excitation contribution to auroral 844.6 nm emission and show that its influence on the peak altitude is not confined to the highest-energy precipitation.

1 Introduction

Auroral emissions are produced when electrons precipitating from the magnetosphere collide with atoms and molecules in the upper atmosphere, causing excitation and ionization followed by radiative de-excitation (e.g., Rees, 1963; Vallance Jones, 1974). The observed emission lines and bands include prompt emissions, which are emitted almost immediately after excitation, and forbidden emissions, which have longer lifetimes because they involve metastable states. Although both types of emissions provide information on precipitating electrons, prompt emissions with short radiative lifetimes more directly trace the spatiotemporal dynamics of electron precipitation.



A representative prompt emission is the 427.8 nm emission of the N_2^+ first negative band. Because the 427.8 nm emission is closely related to energy deposition in the atmosphere by precipitating electrons (Rees and Luckey, 1974), it has been widely used in optical observations as a reference emission for constraining the energy flux of precipitating electrons. Rees and Luckey (1974) quantified the relationship between precipitating electron spectra and auroral emission intensities using electron transport calculations, providing the basis for estimating the characteristic energy of precipitating electrons from emission intensities at multiple wavelengths, including 427.8 nm. More recently, Robert et al. (2023) showed through model calculations that the column-integrated intensity of the 427.8 nm emission along the field line is primarily sensitive to the energy flux of precipitating electrons, whereas the peak altitude of the volume emission rate (VER) is sensitive to the mean energy of the electron spectrum. Thus, not only the intensity but also the altitude distribution of the 427.8 nm emission provides an independent observational quantity for diagnosing precipitating electrons.

Estimating auroral emission altitudes generally requires simultaneous observations of the same auroral structure from at least two sites, which in turn requires suitable weather conditions at both sites and makes such observations more difficult than single-site observations. To infer the energy of precipitating electrons from a single site, intensity ratios between emissions at different wavelengths have therefore been widely used. In particular, the intensity ratio between 427.8 nm and OI 630.0 nm has been used for this purpose, because the 630.0 nm emission is generally bright and easy to observe and is associated with lower-energy electron precipitation than the 427.8 nm emission (e.g., Rees and Luckey, 1974; Kaila, 1989; Adachi et al., 2017). However, the 630.0 nm emission is a forbidden emission from the metastable $O(^1D)$ state and can exhibit response times of several tens of seconds even when collisional quenching is taken into account (Ono and Hirasawa, 1992). It is therefore not ideal for diagnosing rapidly varying electron precipitation.

To avoid this limitation in temporal response, the prompt atomic oxygen emissions OI 777.4 nm and OI 844.6 nm have been used. Because these emissions can follow rapid variations in electron precipitation, they are well suited for high-time-resolution diagnostics of electron precipitation (Lanchester et al., 2009; Nozawa et al., 2018). However, the 777.4 nm emission lies close in wavelength to the strong N_2 first positive band and can therefore suffer substantial contamination, introducing systematic uncertainty when quantitatively interpreting atomic oxygen emission (Oyama et al., 2018). In this respect, the 844.6 nm emission has the advantage of providing a more selective measurement of atomic oxygen emission than the 777.4 nm emission.

From this perspective, the combination of N_2^+ 427.8 nm and OI 844.6 nm provides a useful optical diagnostic of electron precipitation. Ono (1993) showed, using observations with a high-speed multichannel photometer and model calculations, that $I_{844.6}/I_{427.8}$ is a useful indicator of the mean energy of precipitating electrons. Subsequently, Gustavsson et al. (2001) combined 427.8 and 844.6 nm observations from the auroral large imaging system (ALIS; Brändström, 2003) to estimate the characteristic energy and energy flux of precipitating electrons. Tanaka et al. (2006) also estimated the precipitating electron spectrum by combining optical emissions at 844.6 and 427.8 nm with cosmic noise absorption measurements from an imaging riometer. Thus, unlike the 630.0 nm emission, the 844.6 nm emission can follow rapid variations in electron precipitation and has been used together with 427.8 nm for optical diagnostics of precipitating electrons.



60 However, the production mechanisms of the 844.6 nm emission are not simple. In addition to direct excitation of atomic oxygen (O) by precipitating electrons, the $O(3p^3P)$ state can also be produced by dissociative excitation of O_2 . Lanchester et al. (2009) discussed these excitation pathways for the 777.4 and 844.6 nm emissions based on multispectral optical observations combined with radar measurements and auroral modeling, and showed that O_2 dissociative excitation increases the sensitivity of atomic oxygen emissions to high-energy electron precipitation. In addition, radiative cascades from higher excited states
65 can also contribute to the 844.6 nm emission (Lanchester et al., 2009). Therefore, the observed column-integrated intensity of the 844.6 nm emission cannot be attributed to a single excitation process in general.

This issue also remains in current electron transport models. Liang et al. (2026) compared emission calculations from TREx-ATM, the Boltzmann 3-Constituent model (B3C; Strickland et al., 1993; Hecht et al., 1999), and the GLObal AirglOW model (GLOW; Solomon, 2017) to investigate the causes of differences in predicted emission intensities and intensity ratios among
70 the models. They noted that the widely used GLOW model includes electron-impact excitation of atomic oxygen for the 844.6 nm emission but does not include dissociative excitation of O_2 . Because the O_2/O ratio increases toward lower altitudes, the influence of the omitted O_2 pathway is expected to grow as precipitating electrons penetrate more deeply. However, this predicted energy dependence has not previously been tested using direct measurements of the 844.6 nm emission altitude. It is therefore difficult to determine from column-integrated intensity ratios alone whether observed variations in the intensity ratio
75 arise from changes in the precipitating electrons or from deficiencies in the model.

Emission altitude provides an independent constraint on this ambiguity, distinct from column-integrated intensity. Because the altitude of energy deposition decreases as the energy of precipitating electrons increases, the emission altitude itself constrains the electron spectrum. In addition, even for the same emission wavelength, the altitude distributions of the production rates may differ when different reaction pathways depend on different neutral atmospheric species, as is the case for the
80 844.6 nm emission. Therefore, by directly measuring the 844.6 nm emission altitude and comparing it with model predictions constrained by the 427.8 nm emission, the validity of the emission model can be tested in a way that is not possible using intensity ratios alone.

The usefulness of emission-altitude measurements as a diagnostic has already been demonstrated for other auroral emissions. Whiter et al. (2023) used a multisite all-sky camera network in northern Finland and Sweden to estimate simultaneous emission
85 altitudes at 557.7 and 427.8 nm over seven winters from 2000 to 2007. Although the mean peak altitudes of the two emissions were both close to 114 km, their altitude difference varied systematically with electron precipitation conditions, showing that comparisons with model calculations can be used to investigate differences in the underlying emission processes. Importantly, the peak altitudes derived from multisite imaging do not depend on the absolute emission intensity. Emission altitude therefore provides an independent constraint for model validation that is fundamentally different from a radiometric intensity ratio.

90 In this study, we use 427.8 and 844.6 nm images obtained with the multisite optical observation network ALIS_4D (Taki et al., 2026) in northern Sweden to estimate the temporal evolution of the peak emission altitudes at both wavelengths. We analyze a single auroral event observed on 22–23 February 2026, consisting of diffuse aurora before and after a substorm, including pulsating aurora and black aurora. We then compare the observed two-wavelength peak-altitude relationship with calculations from two electron transport models with different formulations. Through this comparison, we test whether O_2



Table 1. Geographic coordinates of the ALIS_4D stations and viewing directions of the cameras used in this study.

Station	Latitude (deg)	Longitude (deg)	Azimuth (deg)	Elevation (deg)
O, Kiruna	67.841	20.411	187.7	77.4
A, Abisko	68.356	18.820	140.4	56.6
S, Silkkimuotka	68.030	21.687	229.8	65.5
T, Tjautjas	67.333	20.751	333.4	79.0
N, Nikkaluokta	67.852	19.003	126.0	71.2

95 dissociative excitation is required to reproduce the 844.6 nm peak altitude and determine how its influence varies with the characteristic energy of the precipitation.

2 Instruments

We used auroral images obtained with ALIS_4D, a multisite optical observation network deployed in northern Sweden. ALIS_4D consists of six EMCCD cameras, each tilted to maximize the overlap of the fields of view among the stations.
 100 At the five stations other than Esrange, the cameras are equipped with diagonal fisheye lenses providing a field of view of approximately 180° along the diagonal. Figure 1 shows the fields of view of the stations and the analysis region used in this study. Within the common field of view of all stations at an altitude of 100 km, we defined a 200 km × 200 km region as the region of interest (ROI). This region is shown by the gray shaded area in Figure 1. Although the auroral emission altitude can in principle be estimated using only two cameras at different locations, observations from a larger number of cameras improve
 105 the estimation accuracy and allow the altitude to be estimated continuously even when some stations are affected by cloud cover.

The ALIS_4D imaging system is synchronized to GNSS signals, allowing images to be acquired simultaneously at all stations. Each camera is also equipped with a filter wheel to sequentially observe multiple auroral emission wavelengths. For the event analyzed in this study, the filter sequence consisted of observations at 427.8 nm, 670 nm (N₂ first positive band), and
 110 844.6 nm, each for approximately 20 s within a 1-min cycle. The temporal resolution and exposure time of each image were both 1.0 s. Because rotation of the filter wheel requires a few seconds, approximately 18 images were obtained during each 20-s observation interval.

The camera at the Esrange station is equipped with a circular fisheye lens and therefore has a different field of view from those at the other stations. In addition, its filter sequence differs from that used at the other five stations. We therefore excluded
 115 the Esrange data from the present analysis. The locations of the stations used in this study and the viewing directions of the cameras are listed in Table 1.

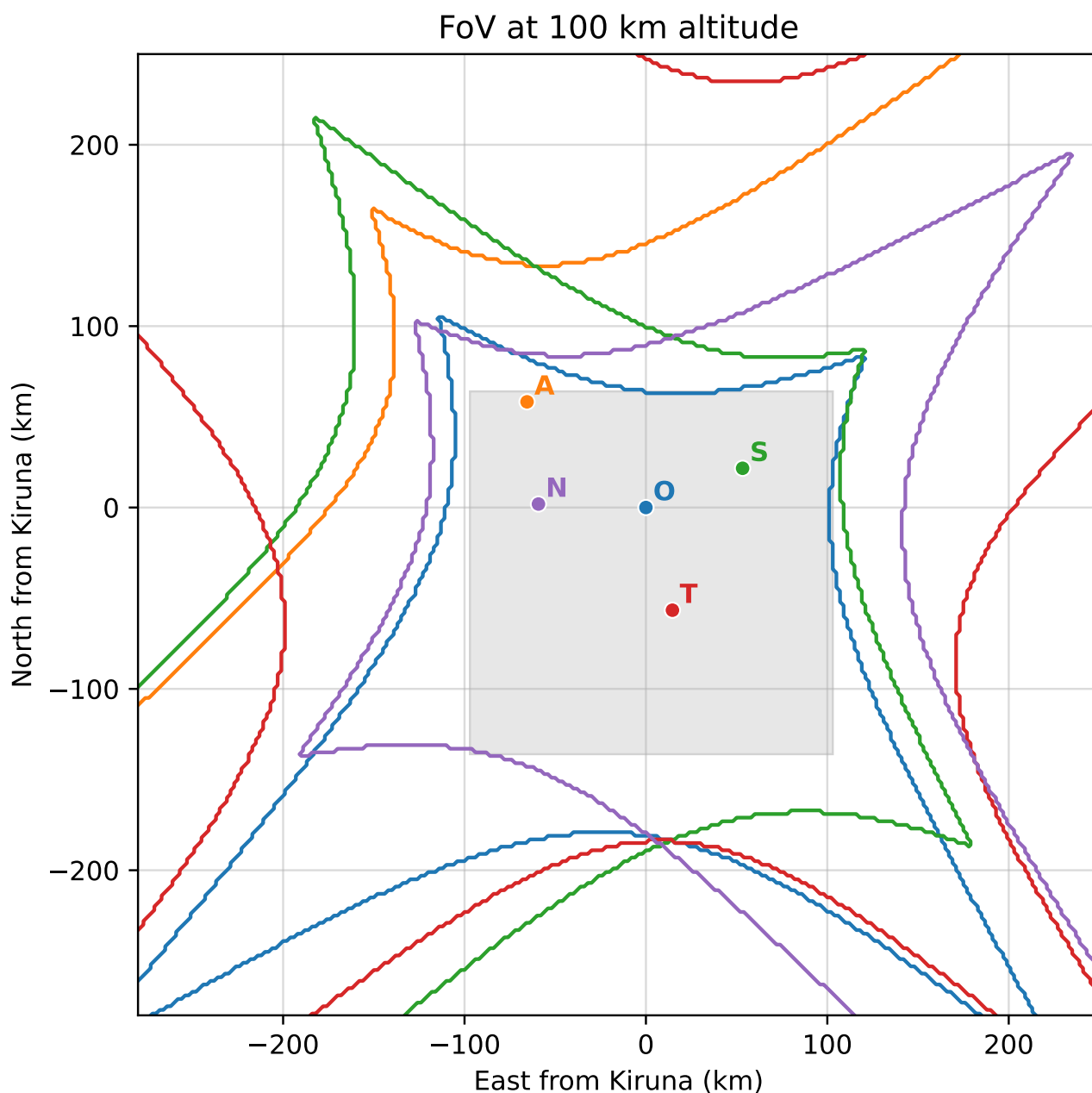


Figure 1. Locations of the ALIS_4D stations and their fields of view at an altitude of 100 km. The station letters, listed in Table 1, are colored to match the corresponding fields of view. The gray hatched 200 km $\times$ 200 km area is visible from all stations at 100 km altitude and is defined as the region of interest (ROI).



3 Analysis

3.1 Altitude estimation by triangulation

The emission altitude was estimated based on the assumption that spatial structures in auroral images acquired simultaneously from multiple stations, particularly boundaries between bright and dark regions, show the best agreement when projected onto the correct altitude. An overview of the method is shown in Figure 2. The five upper panels show raw images obtained at stations A, O, S, N, and T. Dark-current and flat-field corrections were first applied to these images. To reduce the effects of differences in sensitivity among the stations and of dead pixels, the corrected intensity of each image was then normalized to the range 0–1 using its 1st and 99.8th percentile values.

To reduce the influence of broad brightness variations and emphasize local spatial contrasts, local-feature images were generated by dividing each image into 3×3 pixel regions, subtracting the mean within each region, and dividing by the standard deviation within that region. This processing enhances relative bright–dark contrasts, including auroral boundaries and fine-scale intensity structures, which provide the spatial information used for triangulation. Step 1 in Figure 2 schematically illustrates the purpose of this processing; the processed local-feature images themselves are not shown.

The projection altitude was varied from 80 to 120 km in 1 km increments. For a given pair of stations, the two local-feature images were projected onto the same candidate altitude on a horizontal plane covering the ROI with a grid spacing of 0.5 km, and the Pearson correlation coefficient between the projected images was calculated within the ROI. This calculation was repeated over the full range of candidate altitudes to obtain a correlation–altitude profile for that station pair. When the assumed altitude is close to the true emission altitude, the same auroral structures viewed from the two stations overlap most closely and the correlation reaches a maximum. At lower or higher assumed altitudes, parallax produces systematic offsets between the projected structures, as illustrated schematically in step 2 of Figure 2.

The same procedure was repeated for all 10 possible station pairs formed from the five stations, yielding the 10 correlation–altitude profiles shown by the gray curves in the lower-left panel of Fig. 2. At each candidate altitude, the 10 correlation coefficients were then averaged (black curve), and the altitude at which the mean correlation coefficient reached its maximum was adopted as the emission altitude. In the example shown here, the mean correlation coefficient peaked near 91 km, and the representative emission altitude at this time was therefore estimated to be 91 km.

The lower-right panel of Fig. 2 shows a multisite composite at the estimated altitude of 91 km, constructed from the observed images. At each grid point, the image from the station viewing that location at the highest elevation angle is displayed. The colored lines mark boundaries at which the contributing station changes, and the station letters identify the corresponding source images. At the estimated altitude, auroral structures remain spatially continuous across these boundaries, supporting the validity of the altitude estimate; examples of such aligned structures are indicated by the arrows. The composite is used for visualization and quality control rather than for calculating the correlation–altitude profiles. Further details about the accuracy of the altitude estimation are provided in Appendix A.

Because the triangulation is based on spatial intensity contrasts rather than absolute brightness, dark structures can also constrain the projection altitude. For intervals containing black aurora, the estimated altitude is interpreted as a representative



altitude of the structured diffuse auroral layer containing the brightness depletions, rather than as a separate emission altitude of the dark regions themselves.

All individual altitude estimates were visually inspected using the composite images. Estimates were rejected when the auroral structures within the ROI were clearly misaligned among the stations, when little or no aurora or no identifiable structure was present, or when the observed morphology made the triangulation ambiguous, such as aurora with substantial horizontal and vertical extent. For each wavelength, the remaining valid altitude estimates within its 20-s observing interval in each 1-min cycle were averaged to obtain a one-minute mean altitude. A paired sample was retained only when valid one-minute mean altitudes were available at both 427.8 and 844.6 nm within the same cycle, yielding 294 paired one-minute samples.

160 3.2 Corrected count ratio

The corrected count ratio, $C_{844.6}/C_{427.8}$, was calculated within a circular region of 2° radius centered on the magnetic zenith at Tjautjas (azimuth 191.223° , zenith angle 12.647°). For each wavelength, we used the mean counts after dark-current and flat-field corrections. Thus, the ratio used in this study is not a ratio of absolute intensities in Rayleighs, but a ratio of corrected counts measured by the same camera. Because ALIS_4D observes the different wavelengths sequentially using a filter wheel, the 427.8 and 844.6 nm observations are not strictly simultaneous. We therefore included only sequences in which the auroral morphology near the magnetic zenith remained stable and the correspondence between the two wavelengths was clear. Further details are provided in Appendix B.

3.3 GLOW model

To relate the observed emission altitudes to the energy of precipitating electrons, we calculated the volume emission rates (VERs) at 427.8 and 844.6 nm using GLOW (version 0.982; Solomon, 2017), which couples two-stream electron transport with ion and neutral chemistry. Following the standard GLOW configuration, the neutral atmosphere was specified by NRLMSISE-00, while the electron density, electron temperature, and ion temperature were provided by IRI-90. The representative calculation was performed for 22 February 2026 at 22 UT and at 67.840°N , 20.410°E . The 81-day mean and daily $F_{10.7}$ values were 138 and 110 sfu, respectively, and A_p was 37.

The relationship between the model input and output is shown in Figure 3. A Maxwellian distribution was assumed for the input electron spectrum, with the characteristic energy E_C varied from 1 to 20 keV. For the Maxwellian parameterization adopted here, the mean energy of the incident electron spectrum is $\langle E \rangle = 2E_C$. The incident spectra were normalized to a total energy flux of $1 \text{ erg cm}^{-2} \text{ s}^{-1}$ (1 mW m^{-2}). The emission peak altitude was defined as the altitude at which the VER reached its maximum. To adequately represent the high-energy tail of the Maxwellian distributions at large E_C , the GLOW electron energy grid was extended from 190 to 240 bins, increasing the upper energy limit from approximately 48 keV to approximately 583 keV. Figure 3a shows the input spectra for $E_C = 5, 10$, and 15 keV, while Figs. 3b and 3c show the resulting VER altitude profiles at 427.8 and 844.6 nm, respectively.

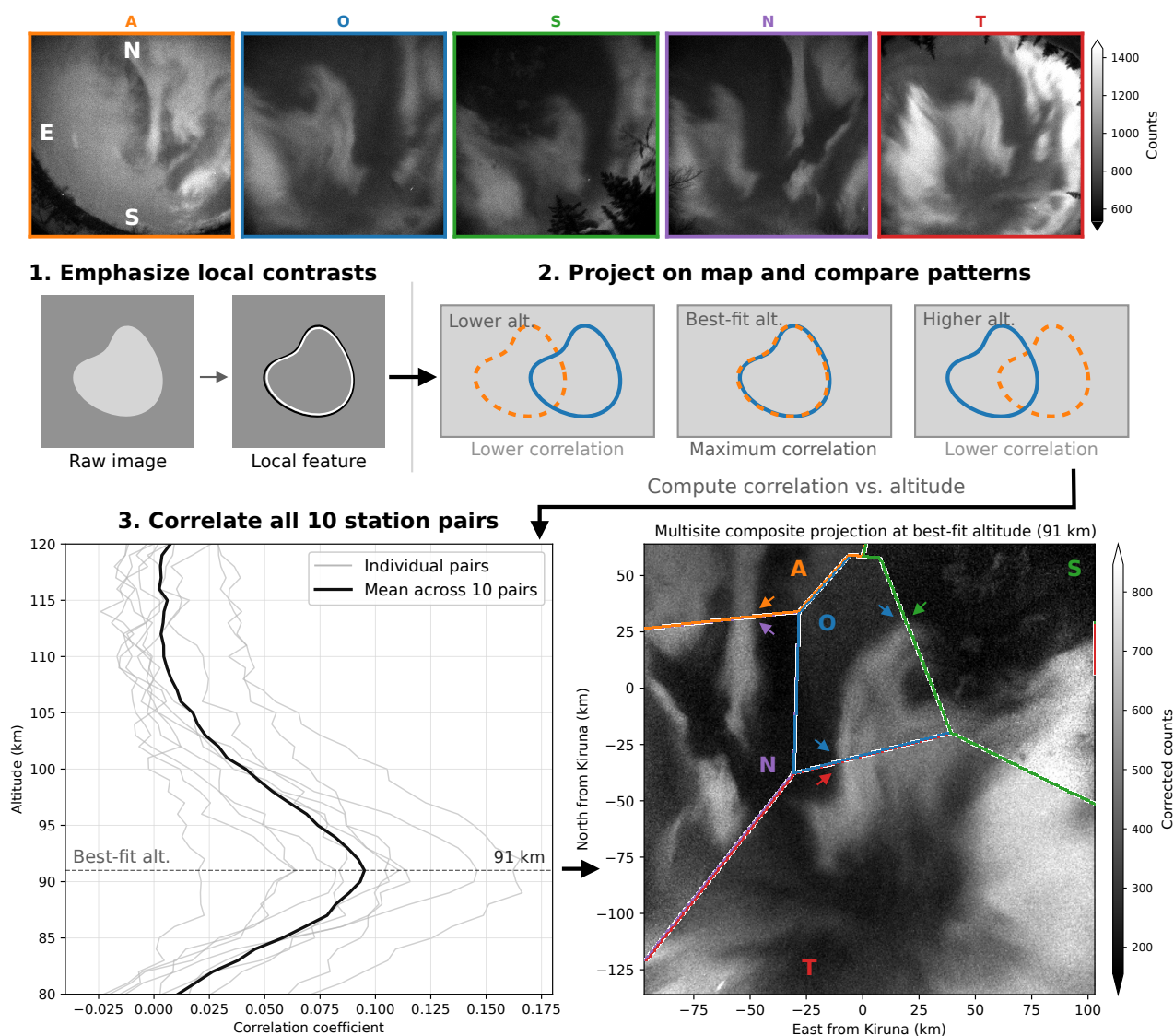


Figure 2. Example of emission-altitude estimation by triangulation. The upper panels show simultaneous raw images from the five stations. Step 1 schematically illustrates the local processing used to emphasize bright–dark contrasts and auroral boundaries. Step 2 illustrates the effect of projection altitude: for each station pair, the two local-feature images are projected onto a series of candidate altitudes and their correlation is calculated at each altitude. The correlation is highest when the same auroral structures are best aligned. In step 3, this procedure is repeated for all 10 station pairs; the gray curves show the resulting correlation–altitude profiles, and the black curve shows their mean, which reaches its maximum at 91 km in this example. The lower-right panel shows a multisite composite of the images projected onto the best-fit altitude. Colored lines indicate boundaries between contributions from different stations, and arrows indicate examples of auroral structures that remain aligned across these boundaries.

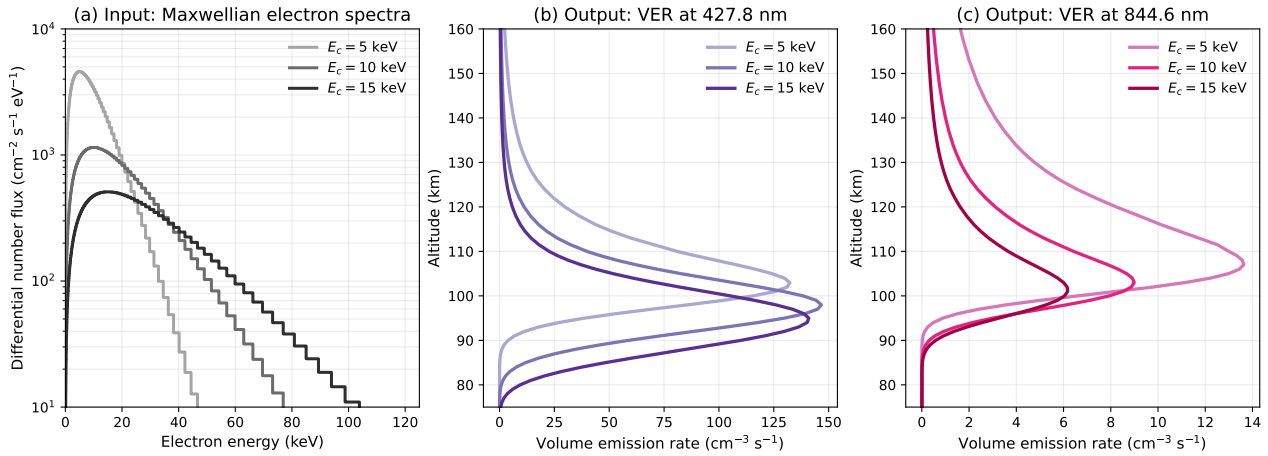


Figure 3. Example of GLOW calculations assuming Maxwellian electron distributions. (a) Incident electron spectra for $E_C = 5, 10$, and 15 keV. (b) 427.8 nm VER profiles. (c) 844.6 nm VER profiles.

3.4 Calculation of O_2 dissociative-excitation term for GLOW

In GLOW v0.982 used in this study, the 844.6 nm VER includes direct electron-impact excitation of atomic O to the $O(3p^3P)$ state and cascade from higher excited states, but does not include production of the same upper state through dissociative excitation of O_2 . To examine the effect of this missing source term on the 844.6 nm emission altitude, we performed a sensitivity calculation using the transported electron flux calculated by GLOW. We used the 844.6 nm emission cross section digitized from Fig. 7 of Schulman et al. (1985) and normalized it to $2 \times 10^{-18} \text{ cm}^2$ at 100 eV. A threshold energy of 16.3 eV was adopted, below which the cross section was set to zero. Between the threshold and 400 eV, the upper limit of the available experimental data, the digitized cross-section values were linearly interpolated onto the GLOW electron energy grid.

For energies above 400 eV, the cross section was extrapolated using the Bethe-type high-energy form

$$\sigma_{844.6}(E) = A \frac{\ln(BE)}{E}, \quad (1)$$

where E is expressed in eV. The parameters A and B were determined by an unweighted least-squares fit to the digitized cross sections between 100 and 400 eV. The fitted curve was subsequently renormalized at 400 eV to ensure continuity with the linearly interpolated experimental cross section. The resulting parameters were $A = 1.54 \times 10^{-16} \text{ cm}^2 \text{ eV}$ and $B = 3.75 \times 10^{-2} \text{ eV}^{-1}$. This extrapolated cross section was evaluated over the remaining GLOW electron energy grid.

At each altitude z , the additional VER was calculated from the sum of the upward and downward electron fluxes computed by GLOW, $\Phi(E, z)$, the O_2 number density, $n_{O_2}(z)$, and the emission cross section, $\sigma_{844.6}(E)$, as

$$\Delta \text{VER}_{844.6}(z) = n_{O_2}(z) \int \Phi(E, z) \sigma_{844.6}(E) dE. \quad (2)$$

This term was added externally to the GLOW 844.6 nm VER; the electron-transport and chemical-reaction calculations were not recomputed. We therefore treat the result as a sensitivity calculation.



3.5 Monte Carlo electron transport and emission model

To test whether the effect of O₂ dissociative excitation on the modeled 844.6 nm peak altitude depends on the electron-transport formulation, we also employed a steady-state Monte Carlo electron transport model based on Sergienko et al. (2012). The model follows the trajectories of primary and secondary suprathermal electrons through successive elastic and inelastic collisions with N₂, O₂, and O. The transported differential electron flux is then used to calculate the altitude profiles of the VERs. To ensure a consistent comparison with the GLOW calculations, the same MSIS and IRI atmospheric and ionospheric profiles were used. The emission profiles were evaluated between 80 and 400 km with an altitude spacing of 0.2 km.

The incident electron spectra were specified using the same Maxwellian distributions and total energy flux of 1 erg cm⁻² s⁻¹ as in the GLOW calculations. The 427.8 nm emission was calculated from electron-impact excitation of N₂⁺. The atomic-O contribution to the 844.6 nm emission included direct excitation of the O(3p³P) state and radiative cascades from higher excited states, following the emission scheme described by Sergienko et al. (2012). The implementation used here additionally includes production of O(3p³P) through dissociative excitation of O₂. Thus, the full 844.6 nm VER can be written as

$$\text{VER}_{844.6}^{\text{full}}(z) = \text{VER}_{844.6}^{\text{O}}(z) + \text{VER}_{844.6}^{\text{O}_2}(z), \quad (3)$$

where $\text{VER}_{844.6}^{\text{O}}$ denotes the combined direct and cascade contributions from atomic O, and $\text{VER}_{844.6}^{\text{O}_2}$ denotes the O₂ dissociative-excitation contribution. For the O₂ dissociative-excitation contribution, we used the same digitized 844.6 nm emission cross section from Schulman et al. (1985) as in the GLOW sensitivity calculation. The same Bethe-type extrapolation above 400 eV was also applied.

Figure 4 shows an example of the calculated 844.6 nm VER profiles for $E_C = 10$ keV. At this characteristic energy, the O₂ dissociative-excitation contribution already produces a distinct lower-altitude component of the 844.6 nm VER. While $\text{VER}_{844.6}^{\text{O}}$ peaks at 103.8 km, inclusion of $\text{VER}_{844.6}^{\text{O}_2}$ shifts the peak of the full emission profile, $\text{VER}_{844.6}^{\text{full}}$, downward by 2.6 km to 101.2 km.

4 Results

4.1 Ground-based observations

Using the method described above, we estimated the temporal evolution of the 427.8 and 844.6 nm emission altitudes for the auroral event observed continuously from dusk to dawn on 22–23 February 2026. An overview of the observations during this night is shown in Fig. 5. Panel (a) shows the horizontal (H) component of the ground magnetic field at Kiruna, located within the ROI. Panels (b) and (c) show keograms constructed from the 427.8 and 844.6 nm images observed at Tjautjas, respectively. Panel (d) shows the emission altitudes at both wavelengths estimated using the method described in Fig. 2. The vertical error bars span the minimum and maximum of the valid individual altitude estimates within each 1-min observing cycle. Intervals A–D indicate periods during which diffuse aurora with similar morphology persisted relatively stably. Black auroral structures, i.e., localized reductions in brightness embedded in diffuse aurora (Gustavsson et al., 2008; Nel et al., 2021), were observed

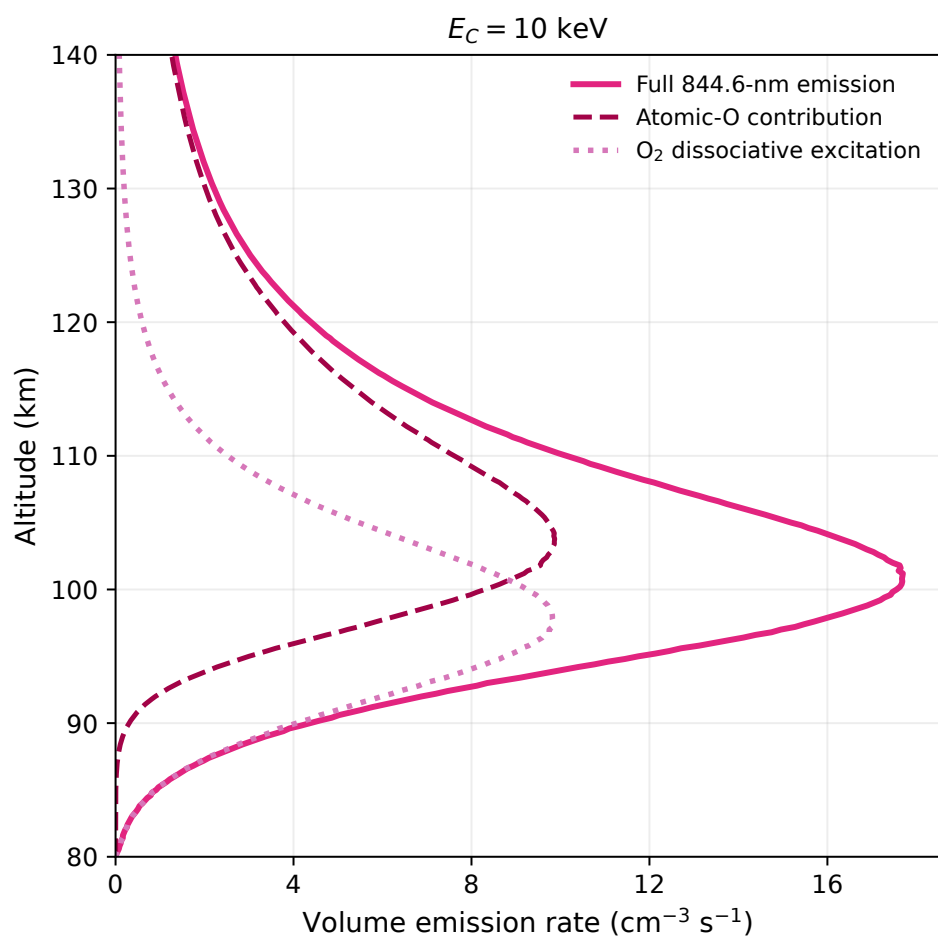


Figure 4. Example decomposition of the 844.6 nm volume emission rate calculated with the Monte Carlo electron transport and emission model for a Maxwellian incident spectrum with $E_C = 10 \text{ keV}$. The solid line shows the full 844.6 nm emission, the dashed line shows the combined atomic-O contribution, and the dotted line shows the O₂ dissociative-excitation contribution. The O₂ contribution peaks at 97.6 km, below the atomic-O contribution at 103.8 km, and shifts the peak of the full profile to 101.2 km.



during interval C, whereas pulsating aurora was dominant during the other intervals. Panel (e) shows the altitude difference between the two wavelengths ($h_{844.6} - h_{427.8}$), and panel (f) shows their corrected count ratio. Because the primary focus of this study is the emission altitudes at the two wavelengths, further details of the auroral morphology during each interval are provided in Appendix C.

Comparison of panels (a)–(c) shows that diffuse aurora was present after the astronomical twilight and in interval A. At approximately 21 UT, the auroral brightness increased rapidly while the H component began to decrease, indicating changes associated with substorm onset. After 21:20 UT, the discrete aurora transitioned to diffuse aurora, and the emission altitudes at both wavelengths decreased by approximately 5–10 km over about 10 min.

During the subsequent interval B, when pulsating aurora was dominant, the 427.8 nm emission altitude remained stable at approximately 92–93 km, while the 844.6 nm altitude remained near 95 km. The altitudes at both wavelengths then gradually increased with time, reaching approximately 105–110 km during interval C, when black aurora was observed. When pulsating aurora again became dominant during interval D, the emission altitudes at both wavelengths decreased to approximately 95 km. Thus, the emission altitudes at both wavelengths varied clearly with the changes in auroral morphology.

In contrast, as shown in panel (e), the relative altitudes of the two emissions remained consistent throughout the event. During the 294 min for which emission altitudes were obtained at both wavelengths, the median value of $h_{844.6} - h_{427.8}$ was 2.0 km, with an interquartile range of 1.0–4.0 km. The 844.6 nm emission was located above the 427.8 nm emission in 83% of the sequences, and the altitude difference showed no clear dependence on auroral morphology.

As shown in panel (f), the corrected count ratio $C_{844.6}/C_{427.8}$ varied more strongly than the altitude difference. The ratio decreased during the low-altitude pulsating aurora intervals B and D and increased during the higher-altitude interval C when black aurora was observed. Thus, the corrected count ratio reflected changes in the emission peak altitude, and hence in the energy of the precipitating electrons, whereas the peak-altitude difference between the two wavelengths remained relatively stable.

4.2 Consistency of the observed two-wavelength peak-altitude relationship with GLOW

To test whether GLOW reproduces the observed relationship between the peak altitudes of the two emissions, we used the observed 427.8 nm peak altitude as a constraint on the penetration depth of the precipitating electrons. Hereafter, h_{λ}^{obs} and $h_{\lambda}^{\text{GLOW}}$ denote the observed and GLOW-calculated peak altitudes at wavelength λ , respectively, and E_C^{inf} denotes the value of E_C inferred from $h_{427.8}^{\text{obs}}$. As shown in Fig. 3, each value of E_C yields a pair of GLOW-calculated peak altitudes, $(h_{427.8}^{\text{GLOW}}, h_{844.6}^{\text{GLOW}})$. At each time for which peak altitudes were obtained at both wavelengths, E_C^{inf} was inferred from $h_{427.8}^{\text{obs}}$ using the GLOW relationship between E_C and $h_{427.8}^{\text{GLOW}}$. The corresponding $h_{844.6}^{\text{GLOW}}$ was then calculated using E_C^{inf} . Figure 6 compares $h_{844.6}^{\text{GLOW}}$ with $h_{844.6}^{\text{obs}}$. The observed 844.6 nm peak altitudes shown in black are the same as those plotted in Fig. 5d, and the two figures use the same time axis.

Because $h_{427.8}^{\text{obs}}$ at each time was used to infer E_C^{inf} , the overall time variation of $h_{844.6}^{\text{GLOW}}$ largely reflects the variation in $h_{427.8}^{\text{obs}}$. The key comparison in Fig. 6 is therefore the remaining difference between $h_{844.6}^{\text{GLOW}}$ and $h_{844.6}^{\text{obs}}$. The two values were relatively close during intervals A and C, when the observed emission altitude was relatively high. In contrast, $h_{844.6}^{\text{GLOW}}$ was

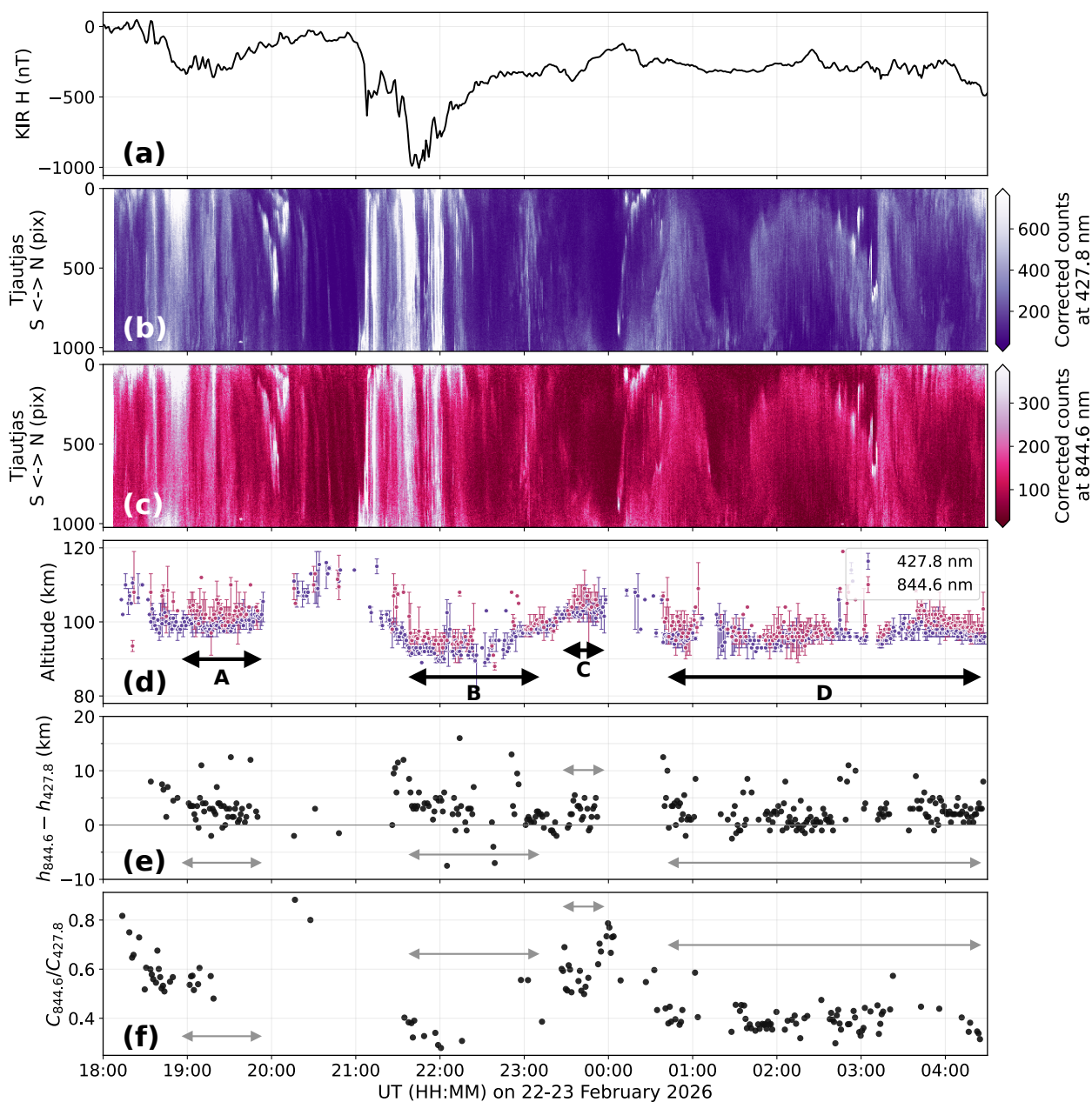


Figure 5. Overview of the observations from 18 UT on 22 February to 04:30 UT on 23 February 2026. (a) Horizontal (H) component of the ground magnetic field at Kiruna. (b, c) Keograms of the 427.8 and 844.6 nm emissions observed at Tjautjas. (d) One-minute mean emission peak altitudes; the vertical bars span the minimum and maximum of the valid individual altitude estimates within each 1-min observing cycle. (e) Altitude difference, $h_{844.6} - h_{427.8}$. (f) Corrected count ratio near the magnetic zenith.

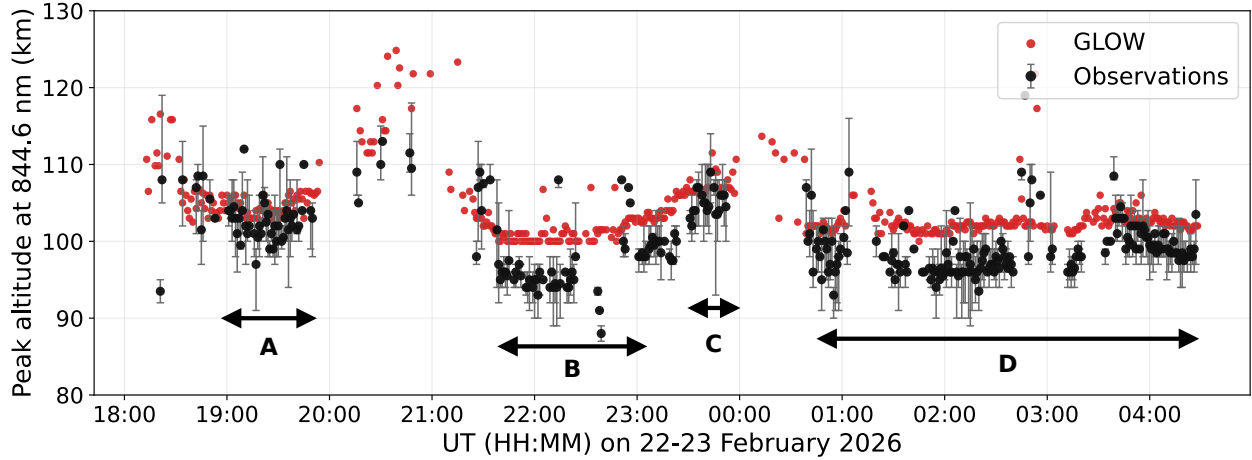


Figure 6. Time-series comparison of the observed and GLOW-calculated 844.6 nm peak altitudes, $h_{844.6}^{\text{obs}}$ (black) and $h_{844.6}^{\text{GLOW}}$ (red). At each time, E_C^{inf} was inferred from $h_{427.8}^{\text{obs}}$, and $h_{844.6}^{\text{GLOW}}$ was calculated using the inferred value. The black points show the one-minute mean observed 844.6 nm peak altitudes, and the vertical bars span the minimum and maximum of the valid individual altitude estimates within each 1-min observing cycle. These observations are the same as those shown in Fig. 5d. The time axis and interval labels A–D are also the same as in Fig. 5.

systematically higher than $h_{844.6}^{\text{obs}}$ during the low-altitude intervals B and D. The time-series comparison therefore shows that the discrepancy persisted during the low-altitude portions of the event rather than appearing only at isolated times.

To quantify this altitude dependence directly, Fig. 7 compares the observed altitude pairs, $(h_{427.8}^{\text{obs}}, h_{844.6}^{\text{obs}})$, with the corresponding altitude pairs calculated by the models. Each position along a model curve represents the pair of peak altitudes calculated for one value of E_C .

As shown by the red solid line in Fig. 7a, GLOW reproduced the overall relationship between the two peak altitudes. As E_C increased, both modeled peak altitudes decreased, while the 844.6 nm peak remained above the 427.8 nm peak. However, the GLOW curve lay increasingly above the observations toward lower values of $h_{427.8}^{\text{obs}}$. For each observation, we interpolated the GLOW curve at $h_{427.8}^{\text{obs}}$ and calculated the model–observation difference as $h_{844.6}^{\text{GLOW}} - h_{844.6}^{\text{obs}}$. Positive values indicate that GLOW placed the 844.6 nm peak above the observed altitude. The median difference was 3.5 km for all 294 measurements. For the lower-altitude subset corresponding to $E_C^{\text{inf}} > 15$ keV, the median difference increased to 5.0 km. Thus, although GLOW reproduced the qualitative relationship between the two wavelengths, the calculation contained insufficient 844.6 nm emission at lower altitudes and consequently produced an increasing high-altitude bias under deeper electron penetration.

280 4.3 Effect of O₂ dissociative excitation on the 844.6 nm peak altitude

The increasing overprediction toward lower altitudes suggests that the GLOW calculation is missing a source of 844.6 nm emission that becomes more important at lower altitudes. In the GLOW version used here, the 844.6 nm VER includes direct

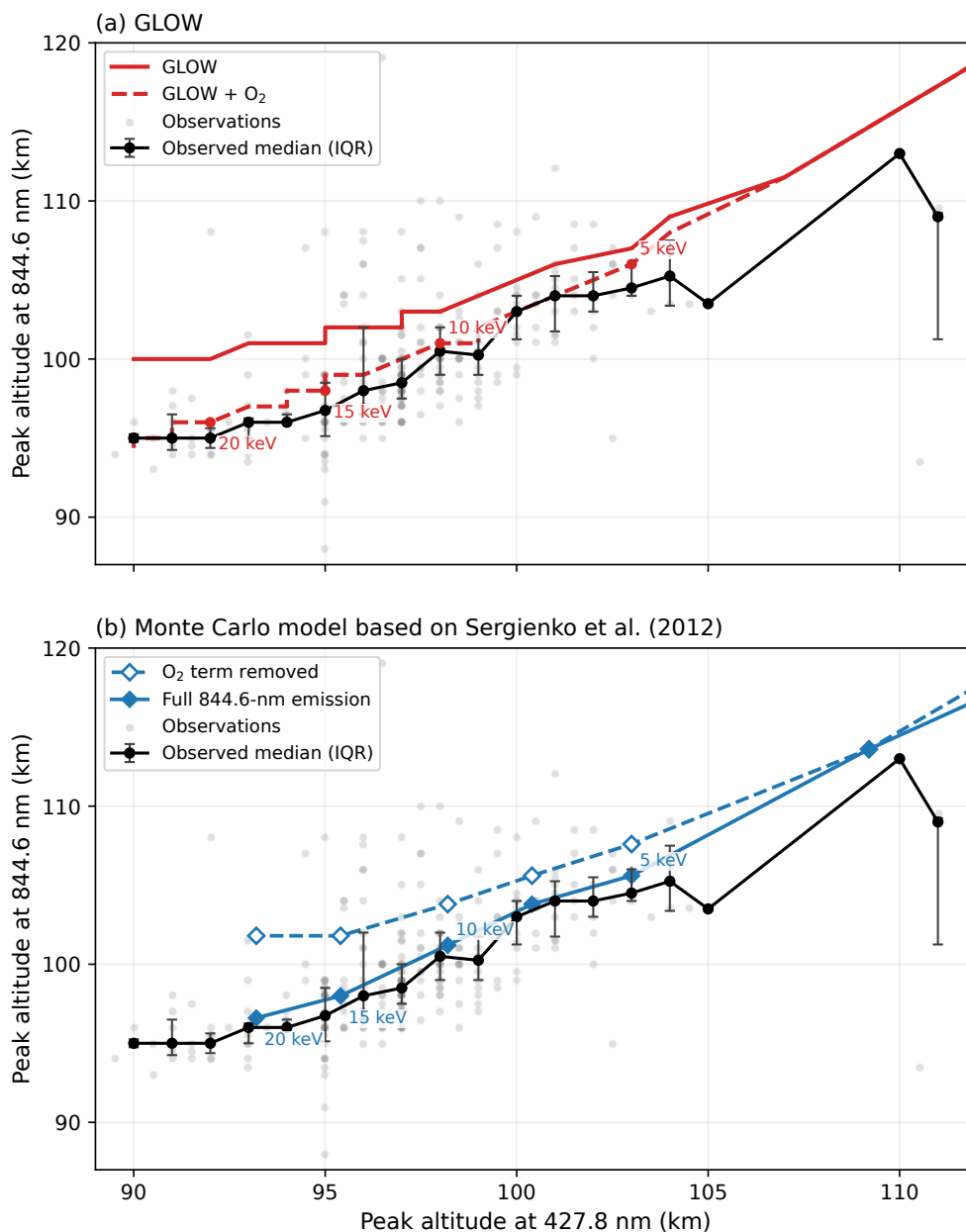


Figure 7. Comparison of the observed 427.8 and 844.6 nm peak altitudes with the calculations from each model. The 294 paired one-minute mean altitude estimates are plotted as gray dots in both panels. The black points and error bars indicate the median and interquartile range of the observed 844.6 nm peak altitude in 1 km bins of the observed 427.8 nm peak altitude. (a) GLOW calculation (red solid line) and the sensitivity calculation including O₂ dissociative excitation (red dashed line). (b) Full Monte Carlo emission calculation (blue solid line and filled diamonds) and the corresponding calculation with the O₂ contribution removed (blue dashed line and open diamonds). The values of E_C used as input to the models are labeled.



electron-impact excitation of atomic O and radiative cascades from higher excited states, but it does not include production of the $O(3p^3P)$ state through dissociative excitation of O_2 . Because O_2 becomes more abundant relative to atomic O toward lower altitudes, this process is expected to have a larger effect when energetic electrons penetrate more deeply. We therefore added the O_2 dissociative-excitation term calculated using Eq. (2) to the GLOW 844.6 nm VER as a sensitivity calculation.

As shown by the red dashed line in Fig. 7a, inclusion of the O_2 contribution shifted the modeled 844.6 nm peak toward lower altitudes. The peak-altitude shift did not exhibit a sharp threshold but increased gradually with E_C . In the GLOW calculation, no shift was obtained at $E_C = 3$ keV, while the shift was approximately 1 km at $E_C = 4$ –5 keV, 2–3 km at $E_C = 6$ –12 keV, and 3–4 km at $E_C = 15$ –20 keV. The effect therefore became apparent at $E_C \simeq 4$ –5 keV, corresponding to $h_{427.8}^{GLOW} \simeq 103$ –104 km, and increased progressively as the electrons penetrated more deeply. For the full data set, the median model–observation difference decreased from 3.5 to 1.0 km, corresponding to a reduction of 71%. For the lower-altitude subset with $E_C^{inf} > 15$ keV, the median difference decreased from 5.0 to 1.0 km, corresponding to a reduction of 80%. The particularly large improvement at $E_C^{inf} > 15$ keV therefore reflects the increasing importance of an effect already present at lower characteristic energies, rather than an effect confined to the hardest precipitation.

We next tested whether this energy dependence was specific to GLOW using the Monte Carlo model with a different electron-transport formulation. As shown in Fig. 7b, removal of the O_2 term shifted the modeled 844.6 nm peak toward higher altitudes at a given 427.8 nm peak altitude. The upward shift increased from 0 km at $E_C = 2.5$ keV to 2.0 km at 5 keV, 2.6 km at 10 keV, 3.8 km at 15 keV, and 5.2 km at 20 keV. Thus, the Monte Carlo calculation also showed that the O_2 contribution begins to affect the peak altitude near $E_C = 5$ keV and becomes progressively more important with increasing E_C . The full calculation consequently followed the observed peak-altitude relationship more closely, particularly toward lower 427.8 nm peak altitudes.

Despite their different electron-transport formulations, the two models showed the same gradual energy dependence: the O_2 -induced shift of the 844.6 nm peak became apparent near $E_C = 5$ keV and increased progressively with E_C . Dissociative excitation of O_2 therefore affects the 844.6 nm peak altitude over a broad range of precipitation energies rather than only under the hardest precipitation, although its effect becomes largest as the electrons penetrate more deeply.

5 Discussion

The low peak altitudes observed during the pulsating-aurora intervals, particularly interval B, are broadly consistent with previous reports of pulsating aurora near 90 km and with statistical evidence that its emission altitude decreases under hard electron precipitation (Brown et al., 1976; Kataoka et al., 2013; Partamies et al., 2017). In contrast, both peak altitudes increased to approximately 105–110 km during interval C, when black auroral structures were embedded in the diffuse emission. Previous observations have associated black auroral structures with a preferential reduction of higher-energy electron precipitation relative to the surrounding diffuse aurora (Peticolas et al., 2002; Gustavsson et al., 2008; Nel et al., 2021), whereas particle and optical observations indicate that pulsating aurora commonly involves electron energies extending from several keV to several tens of keV (Sandahl et al., 1980; Sato et al., 2002; Miyoshi et al., 2010; Samara et al., 2015; Kawamura et al., 2020). The



315 higher emission altitudes during interval C are therefore consistent with a relative softening of the electron precipitation as the auroral morphology changed from pulsating aurora to black aurora during the recovery phase.

The peak altitudes at the two wavelengths remained closely coupled, while the 844.6 nm peak was typically about 2 km higher. Their common variation over approximately 90–110 km indicates that both peak altitudes were mainly controlled by the altitude distribution of energy deposition by the same precipitating electron population. At the same time, the small but
320 persistent altitude difference indicates that wavelength-specific production processes modified their relative VER distributions. As demonstrated for the 557.7 and 427.8 nm emissions by Whiter et al. (2023), relative emission altitudes provide a constraint on emission processes that does not depend on absolute radiometric calibration. The simultaneous decrease in the corrected count ratio $C_{844.6}/C_{427.8}$ during the low-altitude intervals was also qualitatively consistent with harder electron precipitation (Ono, 1993; Tanaka et al., 2006), providing an independent check on the interpretation of the altitude variations.

325 After $h_{427.8}^{\text{obs}}$ was used to constrain the penetration depth, GLOW still placed the 844.6 nm peak increasingly too high toward lower values of $h_{427.8}^{\text{obs}}$. This altitude-dependent residual identifies insufficient low-altitude 844.6 nm emission rather than a failure to reproduce the overall penetration depth of the precipitation.

A likely source of this missing low-altitude emission is dissociative excitation of O_2 . The upper state of the 844.6 nm emission, $\text{O}(3p^3P)$, can be produced through both electron-impact excitation of atomic O and dissociative excitation of O_2 .
330 These pathways and their effects on auroral atomic-oxygen emissions have been examined in spectroscopic, laboratory, observational, and modeling studies (Christensen et al., 1978; Schulman et al., 1985; Lanchester et al., 2009; Grubbs II et al., 2018). In particular, Lanchester et al. (2009) showed that the O_2 pathway increases the response of atomic-oxygen emissions to high-energy electron precipitation. More recently, Liang et al. (2026) found that GLOW, B3C, and TREx-ATM produced relatively similar 427.8 nm emissions but substantially different $I_{844.6}/I_{427.8}$ ratios under high-energy precipitation and large
335 O_2/O conditions. GLOW, which does not include O_2 dissociative excitation in its 844.6 nm calculation, predicted the weakest emission. These previous studies provide a physical explanation for why omission of the O_2 pathway produces an increasingly large high-altitude bias as the precipitation penetrates more deeply. The present calculations further show that this peak-altitude effect is not confined to the highest-energy regime: it becomes apparent at $E_C \simeq 4\text{--}5$ keV and increases progressively with E_C .

340 Adding the O_2 dissociative-excitation contribution using the laboratory cross section of Schulman et al. (1985) and its Bethe-type high-energy extrapolation shifted the GLOW 844.6 nm peak downward and reduced the median model–observation difference by 71% for the full data set and by 80% for $E_C^{\text{inf}} > 15$ keV. The adopted cross section was based on laboratory measurements and was applied in the same way at all values of E_C ; it was not adjusted to reproduce the observed altitudes. The improvement increased progressively toward lower 427.8 nm peak altitudes. The especially large reduction in the discrepancy
345 for $E_C^{\text{inf}} > 15$ keV therefore reflects the increasing magnitude of an O_2 effect that is already present near $E_C = 5$ keV, rather than a process that becomes relevant only under the hardest precipitation. The Monte Carlo model, which used the same O_2 cross-section data but a different electron-transport formulation, showed the same systematic effect: removing only the O_2 contribution shifted the modeled 844.6 nm peak upward, particularly at higher E_C , whereas the full calculation followed the observed peak-altitude relationship more closely. This agreement therefore shows that the direction and altitude dependence



350 of the O₂-induced peak shift are not specific to the GLOW transport formulation and supports the interpretation that O₂ dissociative excitation supplies a substantial lower-altitude component of the 844.6 nm emission.

The present comparison does not, however, uniquely determine the fraction of the 844.6 nm emission produced through O₂ dissociative excitation. Published models use O₂ dissociative-excitation cross sections that differ by up to approximately 40% (Liang et al., 2026). The magnitude of the calculated O₂ contribution therefore depends on the adopted cross-section values, particularly their peak values. The relative importance of the atomic-O and O₂ pathways also depends on the neutral composition, particularly the O₂/O ratio and the uncertain atomic-oxygen density at low altitudes. In addition, the models assume a Maxwellian incident spectrum, whereas a different spectral shape would modify the VER profiles at both wavelengths. Although the two models use different transport formulations, they share the same O₂ cross-section data, atmospheric profiles, and Maxwellian input spectra. Their agreement therefore tests the robustness of the peak-altitude response to the transport formulation, but it does not constrain uncertainties in these shared inputs. The results therefore constrain the effect of the O₂ pathway on the peak altitude more robustly than its exact quantitative contribution to the total 844.6 nm intensity.

The central advance of this study is the use of the observed 427.8 nm peak altitude to constrain the precipitating-electron input and the relative 844.6 nm peak altitude to test wavelength-specific production processes. This helps break the degeneracy between precipitating-electron energy and wavelength-specific emission processes that remains when only column-integrated intensity ratios are used. To our knowledge, the results provide the first altitude-based observational evidence for an O₂ dissociative-excitation contribution to auroral 844.6 nm emission, while showing that its influence on the peak altitude becomes apparent near $E_C = 5$ keV and increases with precipitation energy. Combining emission-altitude measurements with absolute radiometric calibration and electron spectra inferred from tomographic VER reconstructions should allow the atomic-O and O₂ contributions to be constrained jointly using intensity and altitude. More broadly, improving these optical diagnostics is necessary for determining how magnetospheric energy is deposited with altitude in the upper atmosphere.

6 Conclusions

Using synchronized narrow-band imaging by ALIS_4D, we tracked the 427.8 and 844.6 nm emission peak altitudes during the diffuse auroral event on 22–23 February 2026. The main conclusions are as follows.

1. The peak altitudes at the two wavelengths varied together over approximately 90–110 km as the auroral morphology changed. During the 294 min for which altitudes were obtained at both wavelengths, the 844.6 nm peak was located above the 427.8 nm peak in 83% of the measurements, with a median altitude difference of 2.0 km.
2. When the observed 427.8 nm peak altitude was used to constrain the penetration depth of the precipitating electrons, GLOW reproduced the overall relationship between the two peak altitudes but increasingly overestimated the 844.6 nm peak altitude toward lower observed 427.8 nm altitudes. The median model–observation difference was 3.5 km for the full data set and increased to 5.0 km for $E_C^{\text{inf}} > 15$ keV.



3. Including O₂ dissociative excitation shifted the modeled 844.6 nm peak toward lower altitudes. The shift became apparent at $E_C \simeq 4\text{--}5$ keV and increased progressively with E_C , reaching several kilometers at $E_C \gtrsim 10$ keV. The median model–observation difference decreased by 71%, from 3.5 to 1.0 km, for the full data set and by 80%, from 5.0 to 1.0 km, for $E_C^{\text{inf}} > 15$ keV. The larger improvement at high E_C occurs because the effect of O₂ dissociative excitation becomes progressively stronger with increasing E_C .

4. The Monte Carlo calculation with a different electron-transport formulation showed the same energy-dependent response: removing the O₂ contribution shifted the modeled 844.6 nm peak toward higher altitudes, with the magnitude of the shift increasing with E_C . This agreement indicates that the gradual increase in the O₂-induced peak shift is not specific to the GLOW transport formulation and supports the conclusion that O₂ dissociative excitation provides a lower-altitude source of the 844.6 nm emission, although its exact quantitative contribution remains uncertain.

These results show that emission-altitude measurements provide an independent constraint on the ambiguity that remains when only column-integrated intensity ratios are used. By using the observed 427.8 nm peak altitude to constrain the penetration depth of the precipitating electrons and the relative 844.6 nm peak altitude to test wavelength-specific production processes, multisite multiwavelength imaging allows the electron input and the emission physics to be evaluated separately without requiring absolute radiometric calibration. To our knowledge, this study provides the first observational evidence based on emission-altitude measurements for an O₂ contribution to the 844.6 nm emission, while demonstrating that its influence on the peak altitude is already apparent near $E_C = 5$ keV and grows systematically as the precipitation hardens.

Data availability. The data from ALIS_4D can be downloaded from <https://alis.irf.se/stdnames/>. The data from the magnetometer in Kiruna can be downloaded from <https://www.irf.se/maggraphs/iaga/>.

400 **Appendix A: Accuracy of altitude estimation**

The validity of the altitude estimation shown in Fig. 2 was evaluated using the same representative time. Figure A1a shows the projected image at the optimal altitude of 91 km, with the yellow line indicating the horizontal slice used for the following analysis. For each station, an intensity profile was extracted along this slice after projection onto each candidate altitude. Panels (c), (d), and (e) compare the station-by-station intensity profiles at 88, 91, and 94 km, respectively. At 91 km (panel d), the major boundaries between bright and dark regions are most closely aligned among the stations, whereas systematic horizontal offsets corresponding to parallax remain at 88 and 94 km (panels c and e).

Using these profiles, for each candidate altitude we determined the horizontal shift required to align the profile from each station with the median profile of the other stations. The root-mean-square (RMS) of the required shifts across the stations was then used as a measure of positional misalignment. As shown in Fig. A1b, the RMS shift reached a minimum near 91 km, consistent with the optimal altitude obtained from the correlation method. This independent measure of positional consistency therefore supports the altitude determined from the image-correlation analysis.

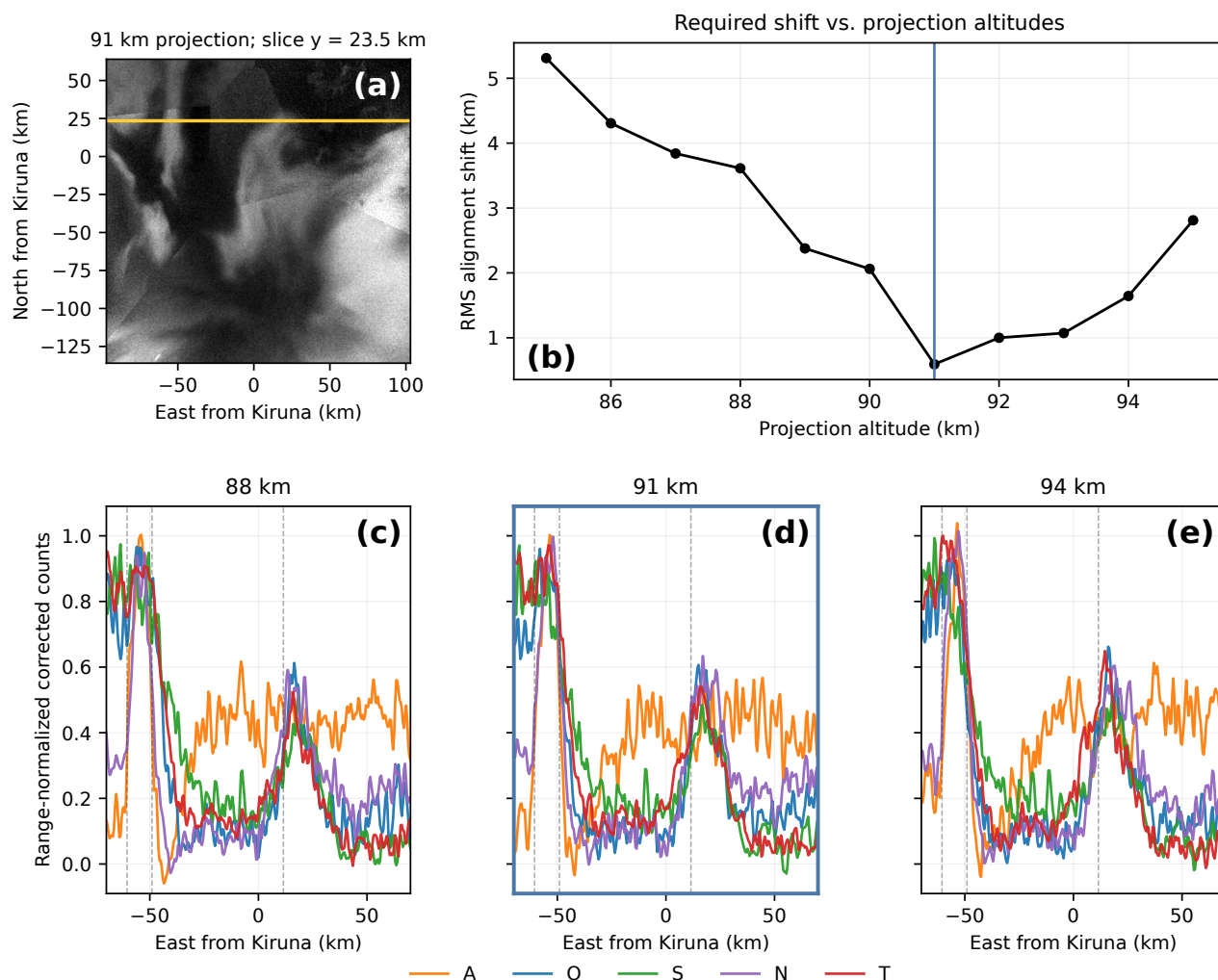


Figure A1. Projection altitude and positional consistency among stations at the same representative time as Fig. 2. (a) Projected image at the optimal altitude of 91 km; the yellow line indicates the horizontal slice used to extract the intensity profiles in panels (c–e). (b) RMS of the horizontal shifts required for alignment as a function of candidate altitude. (c–e) Station-by-station intensity profiles projected onto 88, 91, and 94 km, respectively.



Appendix B: Count ratio selection

The corrected count ratio $C_{844.6}/C_{427.8}$ was calculated from corrected counts within a circular region of 2° radius centered on the magnetic zenith at Tjautjas. For each 427.8 and 844.6 nm frame, the dark current was subtracted and the flat-field correction was applied. Because the two wavelengths were not observed simultaneously, only sequences in which the major auroral structures near the magnetic zenith remained stable were included.

Figure B1 shows an example around 02:40 UT. Although the 427.8 and 844.6 nm images (panels a and b) are separated by approximately 22 s, the major structures near the magnetic zenith correspond well between the two wavelengths. In addition, panels (c) and (d) show that the temporal variations characteristic of pulsating aurora were repeated in a stable manner. The ratio was calculated for 143 sequences exhibiting such spatiotemporally stable morphology. The $C_{844.6}/C_{427.8}$ ratio used here is not an absolute intensity ratio in Rayleighs, but a relative ratio of corrected counts measured by the same imaging system. Therefore, in this study we discuss only its qualitative temporal variation and its correspondence with changes in emission altitude, rather than interpreting its absolute value quantitatively.

Appendix C: Auroral morphology during intervals A–D

Here, we provide additional information on the auroral morphology observed during intervals A–D in Fig. 5, during which similar auroral morphologies persisted and the emission altitudes were relatively stable. Figure C1 shows the pulsating aurora observed at 427.8 nm at 19:31:00 UT, corresponding to interval A. The figure is shown in the same format as the lower-right panel of Fig. 2. The altitude estimated from the correlation analysis was 97 km, which is representative of interval A. A bright patch-like structure is visible in the lower-left part of the image, while relatively dark regions and regions near the background level are observed elsewhere.

Figure C2 shows the analysis of the 427.8 nm image observed at 21:52:00 UT during interval B. The format is the same as that of Fig. C1. The estimated emission altitude was 91 km. Interval B corresponds to the period after substorm onset, and compared with Fig. C1, bright and clearly defined patches of pulsating aurora were observed at a lower altitude.

Figure C3 shows the analysis of the 427.8 nm data observed at 23:40:00 UT during interval C. The estimated emission altitude was 105 km, higher than those in Figs. C1 and C2. During this interval, diffuse aurora containing black auroral structures was observed instead of the pulsating aurora dominant in the preceding intervals. The white region in the lower part of the image does not indicate saturation; instead, the displayed intensity range was narrowed to emphasize the fine-scale bright and dark structures near the center of the image that are characteristic of black aurora. As in Figs. C1 and C2, these structures show good spatial alignment across the boundaries between the station contributions, supporting the validity of the estimated altitude. Thus, during interval C, the diffuse auroral emission containing the black auroral structures was located at a higher altitude than the pulsating auroral emission in the preceding intervals.

Figure C4 shows the analysis of the 427.8 nm data observed at 03:13:00 UT during interval D. Pulsating aurora was again observed. The diffuse auroral emission during interval D was approximately twice as bright as that during interval C, although

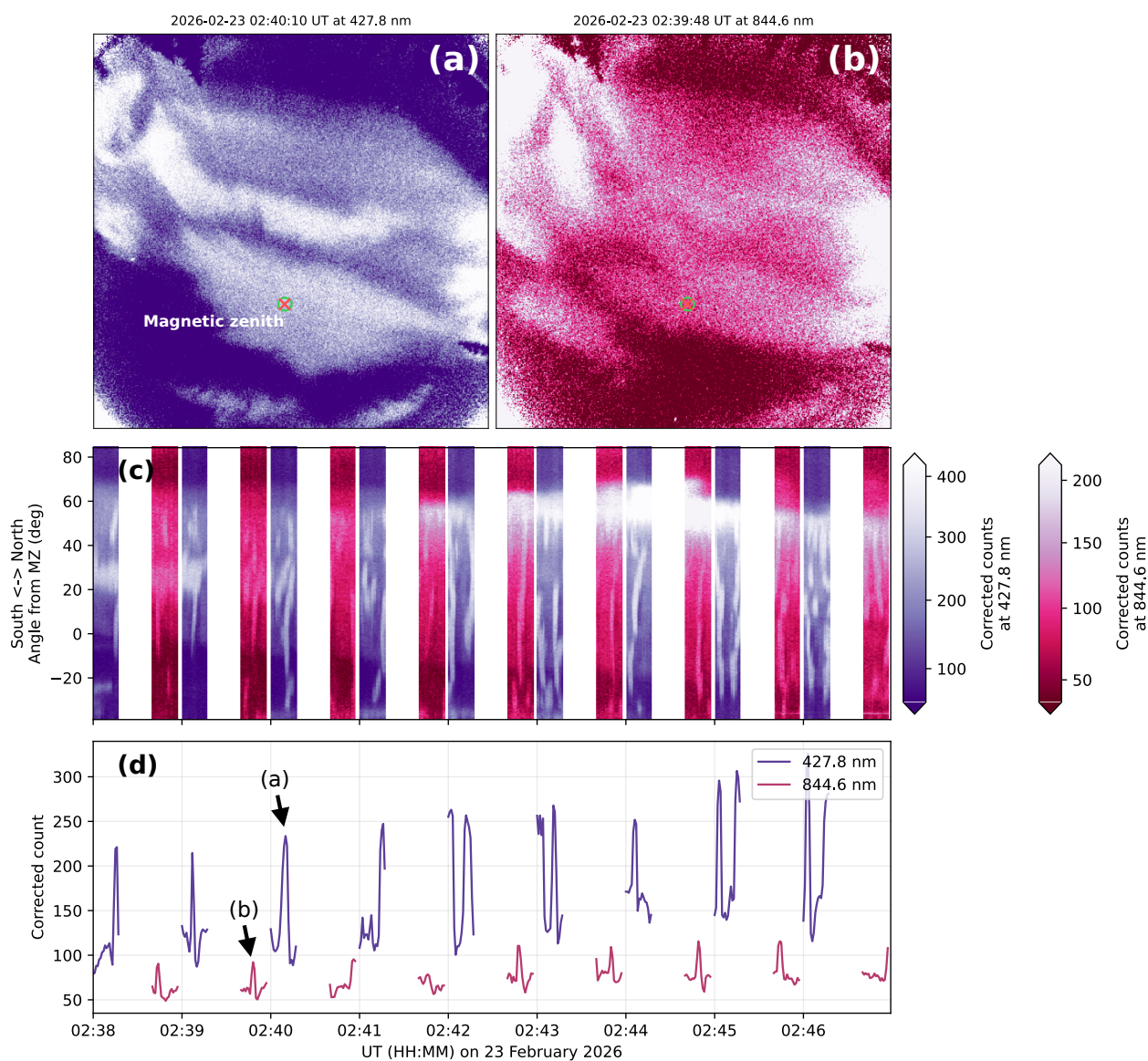


Figure B1. Example of the correspondence between the 427.8 and 844.6 nm emissions near the magnetic zenith at Tjautjas. The upper panels show representative images at each wavelength, the middle panels show the temporal variations within the same 1-min sequence, and the lower panels show the corrected counts within a 2° radius of the magnetic zenith.

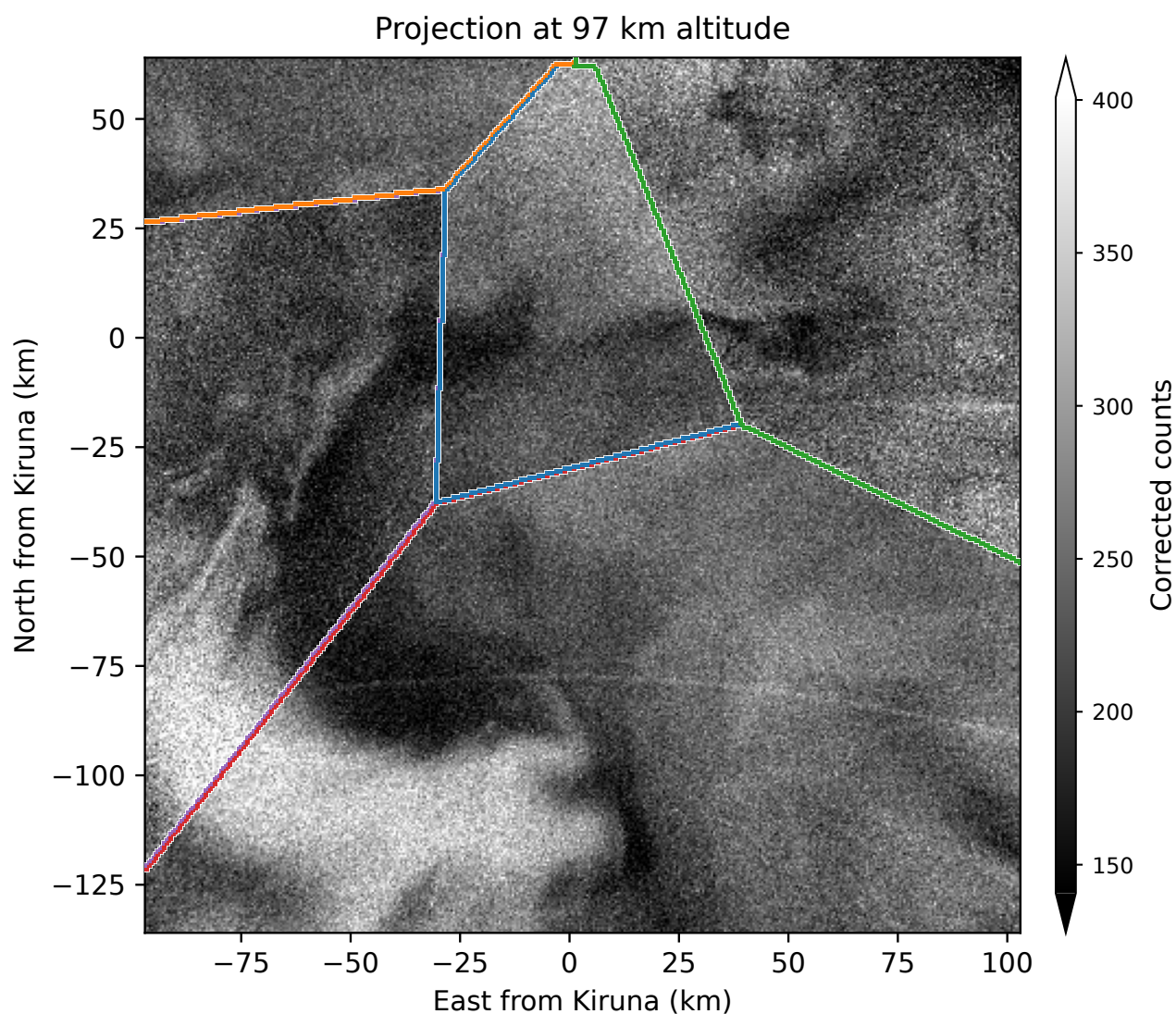


Figure C1. Pulsating aurora observed at 19:31 UT on 22 February 2026 during interval A. The estimated 427.8 nm emission altitude was 97 km.

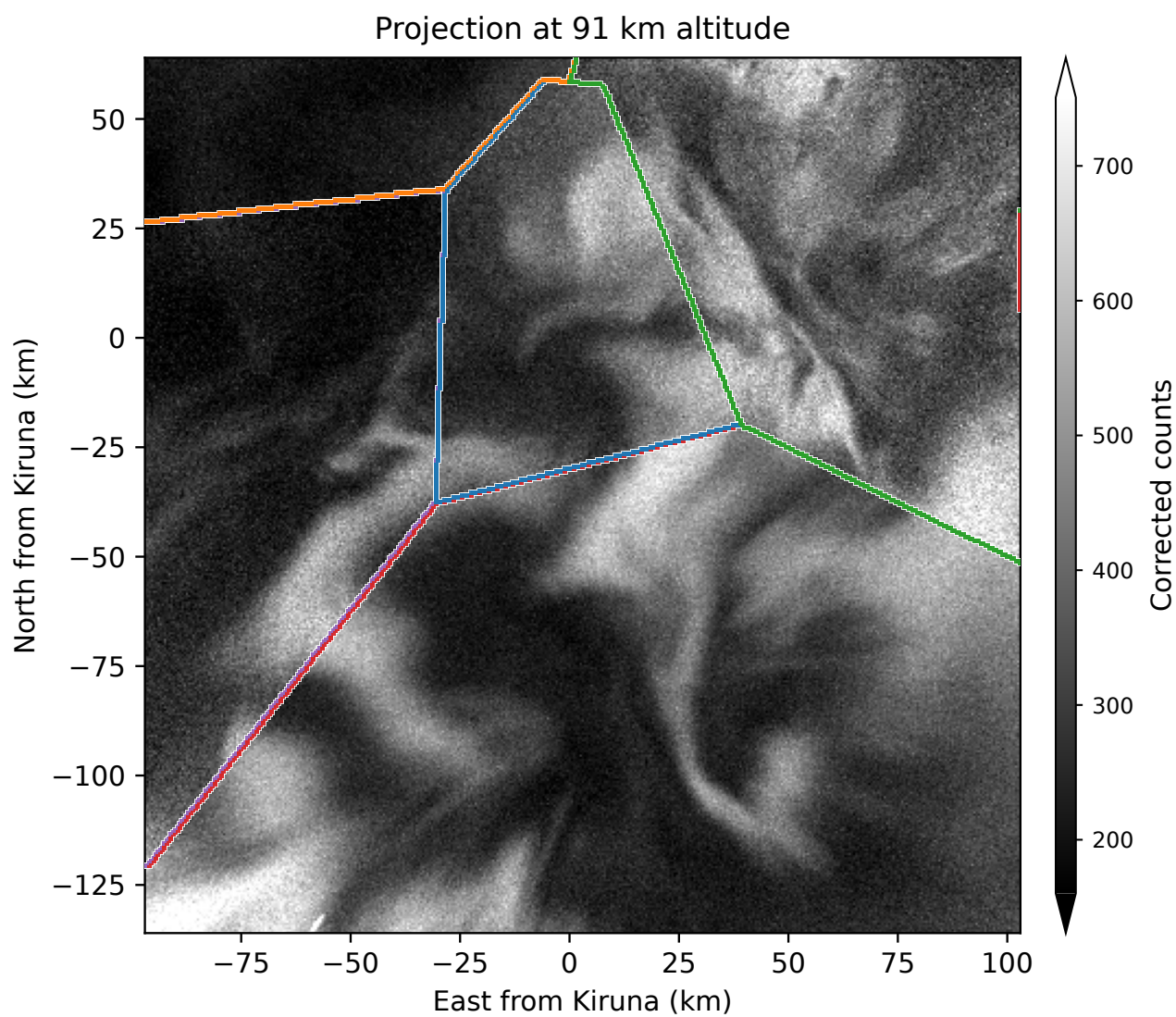


Figure C2. Pulsating aurora observed at 21:52 UT on 22 February 2026 during interval B. The estimated 427.8 nm emission altitude was 91 km.

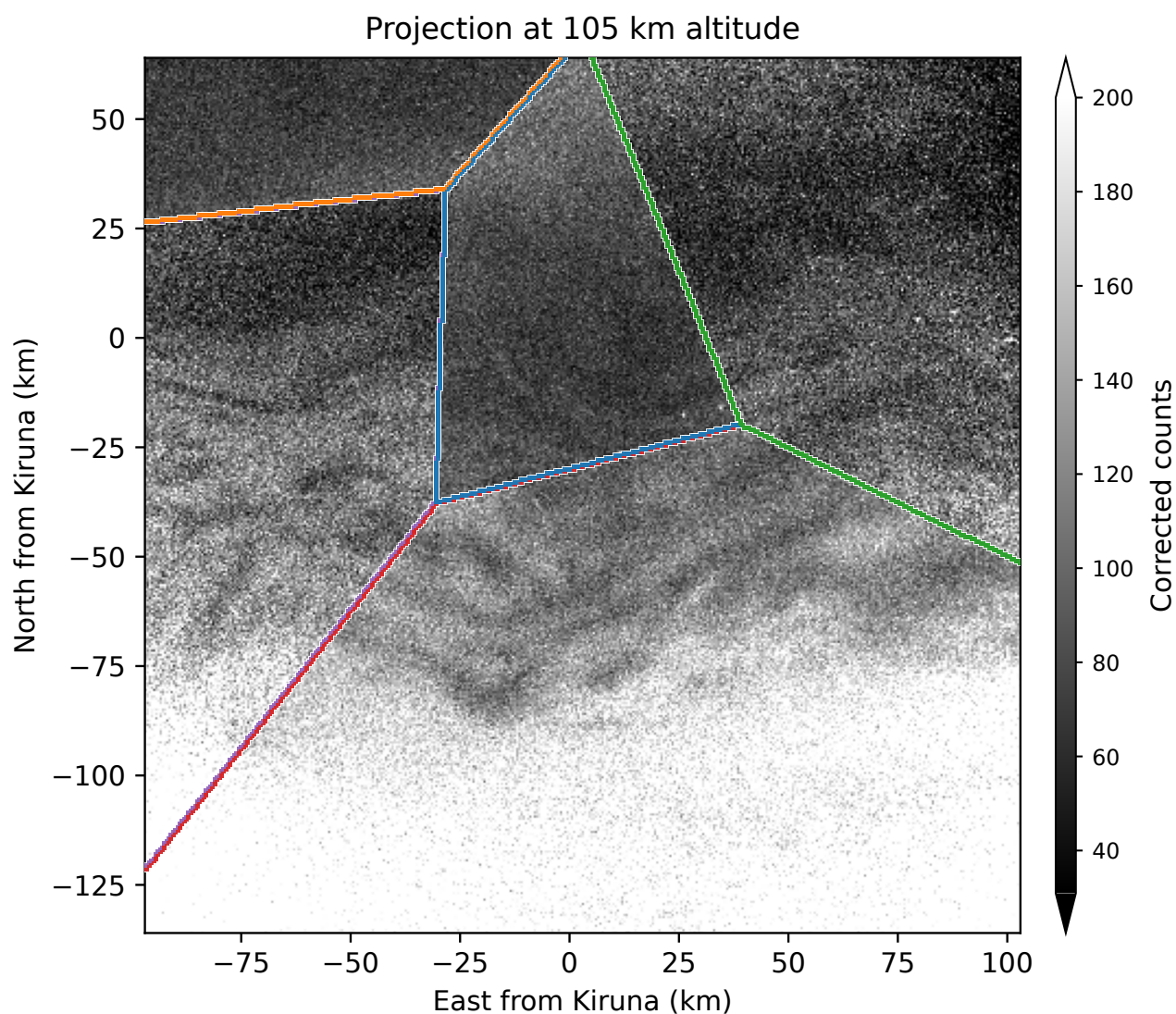


Figure C3. Diffuse aurora containing black auroral structures observed at 23:40 UT on 22 February 2026 during interval C. The estimated 427.8 nm emission altitude was 105 km.

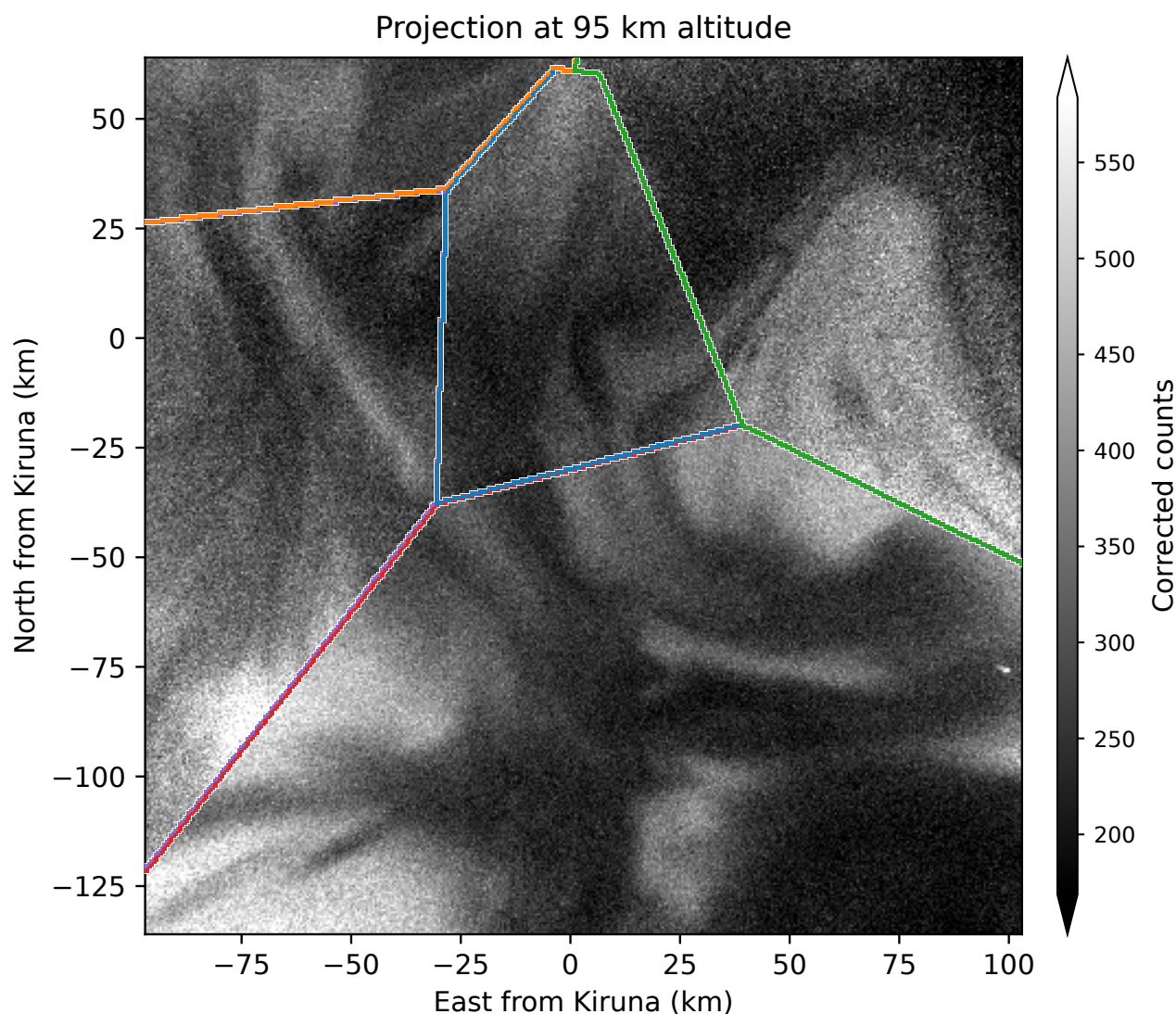


Figure C4. Pulsating aurora observed at 03:13 UT on 23 February 2026 during interval D. The estimated 427.8 nm emission altitude was 95 km.

it remained fainter than during interval B. The estimated emission altitude was approximately 95 km, lower than during interval
 445 C but higher than during interval B.

In summary, the pulsating aurora observed during interval B after substorm onset had the lowest emission altitude and the highest brightness among the four intervals. Pulsating aurora was also observed during intervals A and D, but at somewhat higher altitudes and lower brightness than during interval B. In contrast, interval C was characterized by the faintest diffuse emission and the highest estimated emission altitude, with black auroral structures embedded in the diffuse emission.



450 *Author contributions.* SN performed most analyses and wrote the first draft of the manuscript. TT and TS conducted the geometrical calibration of the cameras and contributed to the interpretation of the results. TT calculated emission profiles by the Monte Carlo based model. UB operated the ALIS_4D observations. All authors approved the final version of the manuscript for submission.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. SN acknowledges support from the Swedish National Space Agency (SNSA; Dnr 2025-00180) and was supported by
455 the Japan Society for the Promotion of Science (JSPS) as a JSPS Overseas Research Fellow during part of this study. ALIS_4D is funded by the Swedish Institute of Space Physics (IRF), Umeå University, the Kempe Foundations, and the Swedish Research Council.



References

- Adachi, K., Nozawa, S., Ogawa, Y., Brekke, A., Hall, C., and Fujii, R.: Evaluation of a method to derive ionospheric conductivities using two auroral emissions (428 and 630 nm) measured with a photometer at Tromsø (69.6°N), *Earth, Planets and Space*, 69, 90, <https://doi.org/10.1186/s40623-017-0677-4>, 2017.
- Brändström, U.: The Auroral Large Imaging System – Design, Operation and Scientific Results, Ph.D. thesis, Swedish Institute of Space Physics, Kiruna, Sweden, iRF Scientific Report 279, 2003.
- Brown, N. B., Davis, T. N., Hallinan, T. J., and Stenbaek-Nielsen, H. C.: Altitude of pulsating aurora determined by a new instrumental technique, *Geophysical Research Letters*, 3, 403–404, <https://doi.org/10.1029/GL003i007p00403>, 1976.
- Christensen, A. B., Rees, M. H., Romick, G. J., and Sivjee, G. G.: O I (7774 Å) and O I (8446 Å) emissions in aurora, *Journal of Geophysical Research: Space Physics*, 83, 1421–1425, <https://doi.org/10.1029/JA083iA04p01421>, 1978.
- Grubbs II, G., Michell, R., Samara, M., Hampton, D., Hecht, J., Solomon, S., and Jahn, J.-M.: A Comparative Study of Spectral Auroral Intensity Predictions From Multiple Electron Transport Models, *Journal of Geophysical Research: Space Physics*, 123, 993–1005, <https://doi.org/10.1002/2017JA025026>, 2018.
- Gustavsson, B., Steen, A., Sergienko, T., and Brändström, B.: Estimate of auroral electron spectra, the power of ground-based multi-station optical measurements, *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science*, 26, 189–194, [https://doi.org/10.1016/S1464-1917\(00\)00106-9](https://doi.org/10.1016/S1464-1917(00)00106-9), 2001.
- Gustavsson, B., Kosch, M. J., Senior, A., Kavanagh, A. J., Brändström, B. U. E., and Blixt, E. M.: Combined EISCAT radar and optical multispectral and tomographic observations of black aurora, *Journal of Geophysical Research: Space Physics*, 113, <https://doi.org/10.1029/2007JA012999>, 2008.
- Hecht, J. H., Christensen, A. B., Strickland, D. J., Majeed, T., Gattinger, R. L., and Jones, A. V.: A comparison between auroral particle characteristics and atmospheric composition inferred from analyzing optical emission measurements alone and in combination with incoherent scatter radar measurements, *Journal of Geophysical Research: Space Physics*, 104, 33–44, <https://doi.org/10.1029/1998JA900009>, 1999.
- Kaila, K.: Determination of the energy of auroral electrons by the measurements of the emission ratio and altitude of aurorae, *Planetary and Space Science*, 37, 341–349, [https://doi.org/10.1016/0032-0633\(89\)90031-7](https://doi.org/10.1016/0032-0633(89)90031-7), 1989.
- Kataoka, R., Miyoshi, Y., Shigematsu, K., Hampton, D., Mori, Y., Kubo, T., Yamashita, A., Tanaka, M., Takahei, T., Nakai, T., Miyahara, H., and Shiokawa, K.: Stereoscopic determination of all-sky altitude map of aurora using two ground-based Nikon DSLR cameras, *Annales Geophysicae*, 31, 1543–1548, <https://doi.org/10.5194/angeo-31-1543-2013>, 2013.
- Kawamura, Y., Hosokawa, K., Nozawa, S., Ogawa, Y., Kawabata, T., Oyama, S.-I., Miyoshi, Y., Kurita, S., and Fujii, R.: Estimation of the emission altitude of pulsating aurora using the five-wavelength photometer, *Earth, Planets and Space*, 72, 96, <https://doi.org/10.1186/s40623-020-01229-8>, 2020.
- Lanchester, B. S., Ashrafi, M., and Ivchenko, N.: Simultaneous imaging of aurora on small scale in OI (777.4 nm) and N₂IP to estimate energy and flux of precipitation, *Annales Geophysicae*, 27, 2881–2891, <https://doi.org/10.5194/angeo-27-2881-2009>, 2009.
- Liang, J., Donovan, E., Spanswick, E., Gabrielse, C., Chaddock, D., and Houghton, J.: Introduction to TREx-ATM V2.0: A Versatile Model of Auroral Transport and Its Effects in the Ionosphere, *Earth and Space Science*, 13, e2026EA005013, <https://doi.org/10.1029/2026EA005013>, 2026.



- Miyoshi, Y., Katoh, Y., Nishiyama, T., Sakanoi, T., Asamura, K., and Hirahara, M.: Time of flight analysis of pulsating aurora electrons, considering wave-particle interactions with propagating whistler mode waves, *Journal of Geophysical Research: Space Physics*, 115, <https://doi.org/10.1029/2009JA015127>, 2010.
- Nel, A. E., Kosch, M. J., Whiter, D., Gustavsson, B., and Aslaksen, T.: A new auroral phenomenon, the anti-black aurora, *Scientific Reports*, 11, 1829, <https://doi.org/10.1038/s41598-021-81363-9>, 2021.
- Nozawa, S., Kawabata, T., Hosokawa, K., Ogawa, Y., Tsuda, T., Mizuno, A., Fujii, R., and Hall, C.: A new five-wavelength photometer operated in Tromsø (69.6°N, 19.2°E), *Earth, Planets and Space*, 70, 193, <https://doi.org/10.1186/s40623-018-0962-x>, 2018.
- Ono, T.: Derivation of Energy Parameters of Precipitating Auroral Electrons by Using the Intensity Ratios of Auroral Emissions, *Journal of geomagnetism and geoelectricity*, 45, 455–472, <https://doi.org/10.5636/jgg.45.455>, 1993.
- Ono, T. and Hirasawa, T.: An Apparent Lifetime of Auroral 630.0nm (OI) Emissions, *Journal of geomagnetism and geoelectricity*, 44, 91–108, <https://doi.org/10.5636/jgg.44.91>, 1992.
- Oyama, S.-i., Tsuda, T. T., Hosokawa, K., Ogawa, Y., Miyoshi, Y., Kurita, S., Kero, A. E., Fujii, R., Tanaka, Y., Mizuno, A., Kawabata, T., Gustavsson, B., and Leyser, T.: Auroral molecular-emission effects on the atomic oxygen line at 777.4 nm, *Earth, Planets and Space*, 70, 166, <https://doi.org/10.1186/s40623-018-0936-z>, 2018.
- Partamies, N., Whiter, D., Kadokura, A., Kauristie, K., Nesse Tyssøy, H., Massetti, S., Stauning, P., and Raita, T.: Occurrence and average behavior of pulsating aurora, *Journal of Geophysical Research: Space Physics*, 122, 5606–5618, <https://doi.org/10.1002/2017JA024039>, 2017.
- Peticolas, L. M., Hallinan, T. J., Stenbaek-Nielsen, H. C., Bonnell, J. W., and Carlson, C. W.: A study of black aurora from aircraft-based optical observations and plasma measurements on FAST, *Journal of Geophysical Research: Space Physics*, 107, SMP 30–1–SMP 30–11, <https://doi.org/10.1029/2001JA900157>, 2002.
- Rees, M. H.: Auroral ionization and excitation by incident energetic electrons, *Planetary and Space Science*, 11, 1209–1218, [https://doi.org/10.1016/0032-0633\(63\)90252-6](https://doi.org/10.1016/0032-0633(63)90252-6), 1963.
- Rees, M. H. and Luckey, D.: Auroral electron energy derived from ratio of spectroscopic emissions 1. Model computations, *Journal of Geophysical Research (1896-1977)*, 79, 5181–5186, <https://doi.org/10.1029/JA079i034p05181>, 1974.
- Robert, E., Barthelemy, M., Cessateur, G., Woelfflé, A., Lamy, H., Bouriat, S., Johnsen, M. G., Brändström, U., and Biree, L.: Reconstruction of electron precipitation spectra at the top of the upper atmosphere using 427.8 nm auroral images, *Journal of Space Weather and Space Climate*, 13, 30, <https://doi.org/10.1051/swsc/2023028>, 2023.
- Samara, M., Michell, R. G., and Redmon, R. J.: Low-altitude satellite measurements of pulsating auroral electrons, *Journal of Geophysical Research: Space Physics*, 120, 8111–8124, <https://doi.org/10.1002/2015JA021292>, 2015.
- Sandahl, I., Eliasson, L., and Lundin, R.: Rocket observations of precipitating electrons over a pulsating aurora, *Geophysical Research Letters*, 7, 309–312, <https://doi.org/10.1029/GL007i005p00309>, 1980.
- Sato, N., Wright, D. M., Ebihara, Y., Sato, M., Murata, Y., Doi, H., Saemundsson, T., Milan, S. E., Lester, M., and Carlson, C. W.: Direct comparison of pulsating aurora observed simultaneously by the FAST satellite and from the ground at Syowa, *Geophysical Research Letters*, 29, 37–1–37–4, <https://doi.org/10.1029/2002GL015615>, 2002.
- Schulman, M. B., Sharpton, F. A., Chung, S., Lin, C. C., and Anderson, L. W.: Emission from oxygen atoms produced by electron-impact dissociative excitation of oxygen molecules, *Phys. Rev. A*, 32, 2100–2116, <https://doi.org/10.1103/PhysRevA.32.2100>, 1985.
- Sergienko, T., Gustavsson, B., Brändström, U., and Axelsson, K.: Modelling of optical emissions enhanced by the HF pumping of the ionospheric F-region, *Annales Geophysicae*, 30, 885–895, <https://doi.org/10.5194/angeo-30-885-2012>, 2012.



- Solomon, S. C.: Global modeling of thermospheric airglow in the far ultraviolet, *Journal of Geophysical Research: Space Physics*, 122, 7834–7848, <https://doi.org/10.1002/2017JA024314>, 2017.
- Strickland, D. J., Daniell Jr., R. E., Jasperse, J. R., and Basu, B.: Transport-theoretic model for the electron-proton-hydrogen atom aurora: 2. Model results, *Journal of Geophysical Research: Space Physics*, 98, 21 533–21 548, <https://doi.org/10.1029/93JA01645>, 1993.
- 535 Taki, T., Sergienko, T., Brändström, U., Ogawa, Y., Nanjo, S., and Araújo, J.: Electric fields in and around an auroral arc and the inferred current system from the BROR sounding rocket experiment, *EGUsphere*, 2026, 1–19, <https://doi.org/10.5194/egusphere-2026-1133>, 2026.
- Tanaka, Y.-M., Kubota, M., Ishii, M., Monzen, Y., Murayama, Y., Mori, H., and Lummerzheim, D.: Spectral type of auroral precipitating electrons estimated from optical and cosmic noise absorption measurements, *Journal of Geophysical Research: Space Physics*, 111, <https://doi.org/10.1029/2006JA011744>, 2006.
- 540 Vallance Jones, A.: *Aurora, Geophysics and Astrophysics Monographs*, D. Reidel Publishing Company, Dordrecht, Holland, ISBN 978-90-277-0272-2, <https://doi.org/10.1007/978-94-010-2099-2>, 1974.
- Whiter, D. K., Partamies, N., Gustavsson, B., and Kauristie, K.: The altitude of green OI 557.7 nm and blue N_2^+ 427.8 nm aurora, *Annales Geophysicae*, 41, 1–12, <https://doi.org/10.5194/angeo-41-1-2023>, 2023.