

ASIS : the Auroral Spectrograph In Skibotn

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Abstract. ASIS (Auroral Spectrograph In Skibotn) is a ground-based spectrograph designed for continuous monitoring and quantitative characterization of visible auroral emissions. Installed at Skibotn Observatory in northern Norway, the instrument combines a Czerny–Turner spectrograph with interchangeable gratings, providing either broad spectral coverage or higher spectral dispersion for dedicated observations of selected auroral features. In its standard configuration, ASIS covers approximately 405–687 nm with a spectral resolution of about 1.2 nm and a temporal resolution of 30 s. We describe the instrument design together with its wavelength and radiometric calibration. Absolute radiometric response curves were derived from calibrated FEL lamps using grating-specific calibration configurations, allowing measured spectra to be converted into absolute spectral brightness in Rayleigh units. Wavelength calibration was performed using Hg–Ar and Ne emission lamps and second-order polynomial fits. Calibrated observations demonstrate the capability of ASIS to resolve the main atomic and molecular auroral emissions, including the N_2^+ first negative bands, the $O(^1S)$ and $O(^1D)$ lines, and Balmer emissions associated with proton precipitation. The calibrated intensities and line ratios can be used to constrain the characteristic energy of precipitating particles and to support coordinated multi-instrument studies of auroral dynamics and energy deposition.

1 Introduction

Ground-based auroral spectroscopy remains one of the most powerful tools for diagnosing magnetosphere–ionosphere coupling and upper atmospheric response to particle precipitation. By resolving discrete atomic and molecular emissions—most prominently the atomic oxygen lines at 557.7 nm and 630.0 nm and the N_2 and N_2^+ band systems—spectroscopic measurements provide quantitative constraints on excitation altitude, characteristic energy of precipitating particles, thermospheric temperature, and neutral winds (Chamberlain, 1961; Vallance Jones, 1974; Rees, 1989).

Over the past decades, major instrumental developments have transformed auroral spectroscopy from single-channel scanning photometers to multi-line imaging spectrographs and high-resolution Doppler instruments. In Canada, the Transition Region Explorer (TReX) network has deployed advanced narrowband imagers and spectrographic systems designed to resolve fine-scale auroral dynamics and transition-region physics (Donovan et al., 2015). Beyond instrumental innovation, TReX has enabled major scientific advances, notably the first detailed spectroscopic characterization of the optical emissions associated with the phenomenon known as STEVE (Strong Thermal Emission Velocity Enhancement). Observations reported by Gillies

25 et al. (2019) demonstrated that STEVE is dominated by a broadband continuum emission distinct from classical auroral precipitation, with weak or absent signatures of typical auroral lines such as 557.7 nm. These results provided compelling evidence that STEVE arises from subauroral ion drifts and extreme ionospheric heating rather than conventional particle precipitation.

At high latitudes, the Svalbard region hosts several long-running optical facilities colocated with radar infrastructure such as EISCAT, allowing coordinated optical–radar studies. Spectrographic and Fabry–Pérot interferometer measurements at Kjell
30 Henriksen Observatory (KHO) and related sites have provided high-resolution observations of thermospheric temperatures and winds derived from auroral and airglow emissions (Conde and Smith, 1995, 1997; Kosch et al., 2010). The synergy between optical spectroscopy and incoherent scatter radar measurements has been particularly important for validating energy deposition estimates and ionospheric heating models. More recently, Tsuda et al. (2020) deployed a temporary spectrographic system near EISCAT and reported detailed spectral observations of unusual auroral structures, highlighting strong subauroral
35 ion drift signatures and atypical emission characteristics. Their results further emphasized the importance of coordinated optical and radar diagnostics for disentangling particle-driven aurora from electrodynamic heating processes.

High-dispersion spectroscopic systems such as the High Throughput Imaging Echelle Spectrograph (HiTIES) have further advanced the field by enabling simultaneous high spectral resolution and spatial coverage (Chamberlain et al., 2003; Conde et al., 2007). These instruments are capable of resolving fine Doppler structure in auroral emission lines, allowing precise
40 retrieval of neutral temperatures, wind velocities, and, in some cases, non-thermal line broadening associated with dynamic auroral processes.

Collectively, these instrumental efforts demonstrate that modern auroral spectroscopy not only refines quantitative diagnostics of classical auroral precipitation but also enables the identification of fundamentally different energy deposition mechanisms, such as subauroral ion drift heating. They highlight the importance of rigorous calibration, accurate instrumental
45 line shape characterization, and coordinated multi-instrument campaigns. Contemporary studies increasingly rely on cross-validation with all-sky imaging, incoherent scatter radar (e.g., EISCAT), and satellite-based particle measurements (e.g., THEMIS, DMSP), reinforcing the central role of optical spectroscopy as the quantitative bridge between observed emissions and modeled particle precipitation spectra.

In this study, we present ASIS (Auroral Spectrograph In Skibotn), a grating spectrograph optimized for observations in the
50 400–700 nm spectral range, with a spectral resolution of $\Delta\lambda \sim 1.2$ nm and a temporal resolution of $\Delta t = 30$ s. Section 2 describes the instrument and its optical design. Section 3 presents the radiometric calibration, including the instrumental response and the conversion to absolute spectral brightness in Rayleighs. Section 4 describes the wavelength calibration. In Section 5, we present a series of calibrated auroral spectra and discuss key scientific applications, demonstrating the instrument’s capability to provide improved quantitative constraints on auroral energy deposition.

55 2 Description of the instrument

ASIS consists of two main subsystems: a light-collecting assembly and a spectrograph–detector unit, optically coupled via a 600 μ m diameter optical fiber. The light is collected by an astronomical lens with a 60 mm aperture and a focal length of

248 mm, providing a circular field of view of approximately 4° . The lens is pointing along the local magnetic field line at an elevation of $\sim 78^\circ$ and an azimuth of $\sim 183^\circ$ (south). A 22 mm diameter reflective collimator is mounted behind the lens and focuses the collected light into an optical fiber, connected via an SMA interface.

The spectrograph is a Czerny–Turner SR303i manufactured by Andor, featuring a focal length of 303 mm, an $f/4$ aperture, and a motorized entrance slit adjustable from $10\mu\text{m}$ to 2.5 mm. A motorized grating turret provides access to three interchangeable gratings (300, 600, and 1800 lines mm^{-1}), enabling operation at different spectral resolutions depending on the scientific requirements. Grating 2 offers only a limited gain in spectral resolution compared with Grating 1, at the expense of a reduced spectral coverage, and was therefore not retained for the observing configurations considered here. In contrast, Grating 3 provides the high spectral resolution required for dedicated observations of selected auroral features.

The optical fiber is coupled to the spectrograph via an adjustable input module (matcher) incorporating two alignment mirrors. A plane mirror tilted at 45° redirects the light emerging from the fiber toward the rear section of the module, where a concave mirror focuses it onto the entrance slit. Both the fiber position relative to the plane mirror and the alignment of the concave mirror can be manually adjusted to ensure accurate imaging of the fiber output onto the slit, thereby maximizing optical throughput.

The dispersed light is recorded by a 16-bit iDus CCD detector manufactured by Andor. The camera features a 1024×256 pixel array and is thermoelectrically cooled to -70°C using a Peltier system to minimize dark current and readout noise.

The SR-303i spectrograph and the iDus CCD camera are operated via a graphical user interface that enables full control of the instrumental settings, including exposure time, slit width, grating selection, mechanical shutter operation, central wavelength, camera temperature, and readout mode. All parameters can be adjusted manually through the control dashboard or programmatically via e.g. a dedicated Python interface.

The instrument was successfully installed in October 2023 at the Skibotn Observatory (lat. $\sim 69.3^\circ$ N, long. $\sim 20.2^\circ$ E). Since then, continuous observations have been conducted using a slit width of $100\mu\text{m}$, an exposure time of 30 s, and grating 1 (300 lines mm^{-1}), providing access to a wavelength range of approximately $[405\text{--}687]\text{ nm}$ (central wavelength $\lambda_c \sim 594\text{ nm}$) with a dispersion $\frac{d\lambda}{dp} \sim 0.3\text{ nm/pixel}$ and a spectral resolution $\Delta\lambda \sim 1.2\text{ nm}$ (measured as the full width at half-maximum (FWHM) of the emission lines). The camera is operated in Full Vertical Binning (FVB) mode in order to integrate the total signal collected along the slit. Acquisition is done automatically using a Python script that calculates ephemerides of the Sun.

3 Radiometric calibration

3.1 General radiometric calibration procedure

Since the spectrograph and detector were already installed in Skibotn as part of a previous instrument configuration (Barthelemy et al., 2019), the radiometric calibration of ASIS was carried out on site in February 2024 and October 2024 using two FEL-type tertiary standards of spectral irradiance (1000 W quartz-halogen lamps). The transfer from secondary to tertiary standards

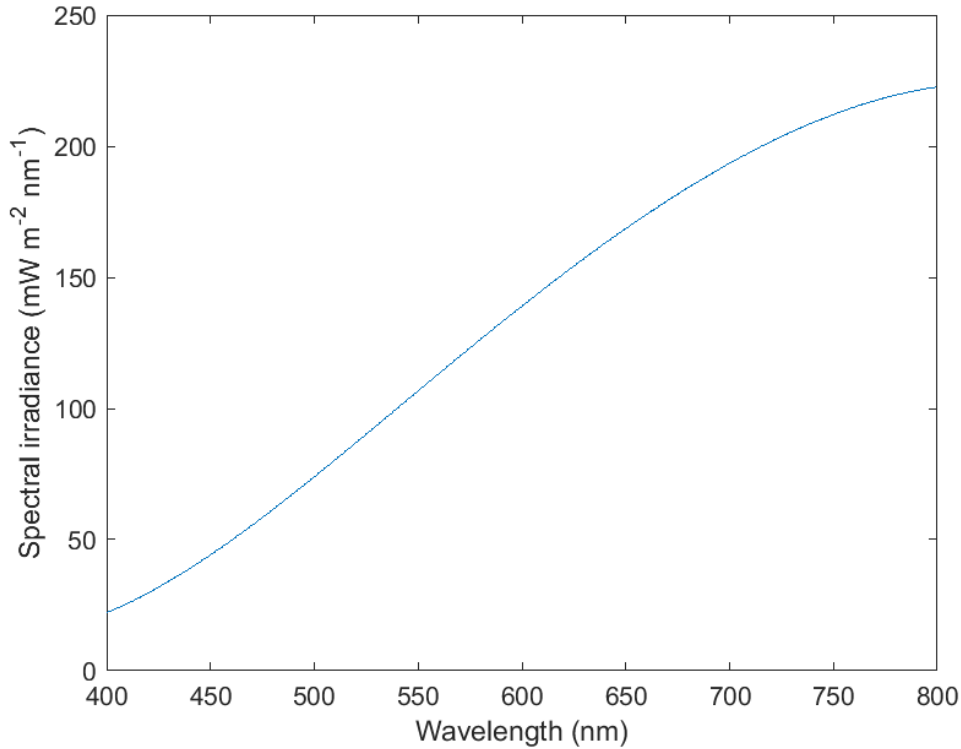


Figure 1. Reference spectral irradiance of FEL Lamp 1 operated at 8 A, measured at a distance of 50 cm from the lamp.

was performed at the Belgian Radiometric Characterization Laboratory (B.RCLab¹) at BIRA-IASB. The nominal operating
 90 current of the FEL lamps is 8 A, stabilized within 1 mA, using a Keysight N5770A power supply. Under these conditions, the
 lamp spectral irradiance is stable to within typically 0.2 %. An example of spectral irradiance (in $\text{mW m}^{-2} \text{nm}^{-1}$) provided by
 the FEL Lamp 1 powered at 8 A and located at 50 cm of the entrance optics / receiver is shown in Fig. 1.

The lamps were carefully aligned along the optical axis of the astronomical lens using a laser reference and a reticle to en-
 sure precise positioning, with a lamp–astronomical lens distance of 99 cm. This setup allowed characterization of the spectral
 95 response of the entire instrument, excluding the acrylic dome. The dome transmittance, based on the manufacturer’s specifica-
 tions, was found to be approximately constant at 92% between 400 and 1000 nm.

All measurements were performed within the linear response regime of the system, both in terms of exposure time (typi-
 cally ≥ 1 s) and recorded signal levels (maximum intensities $\leq 60,000$ ADU). Each measurement was repeated at least 20
 consecutive times to assess the stability of the whole system, and the results were then averaged to increase signal-to-noise
 100 ratio (SNR). The room was darkened as much as possible to minimize stray light. Dark frames (with the camera’s mechanical
 shutter closed) were obtained under the same conditions.

¹<https://brclab.aeronomie.be/>

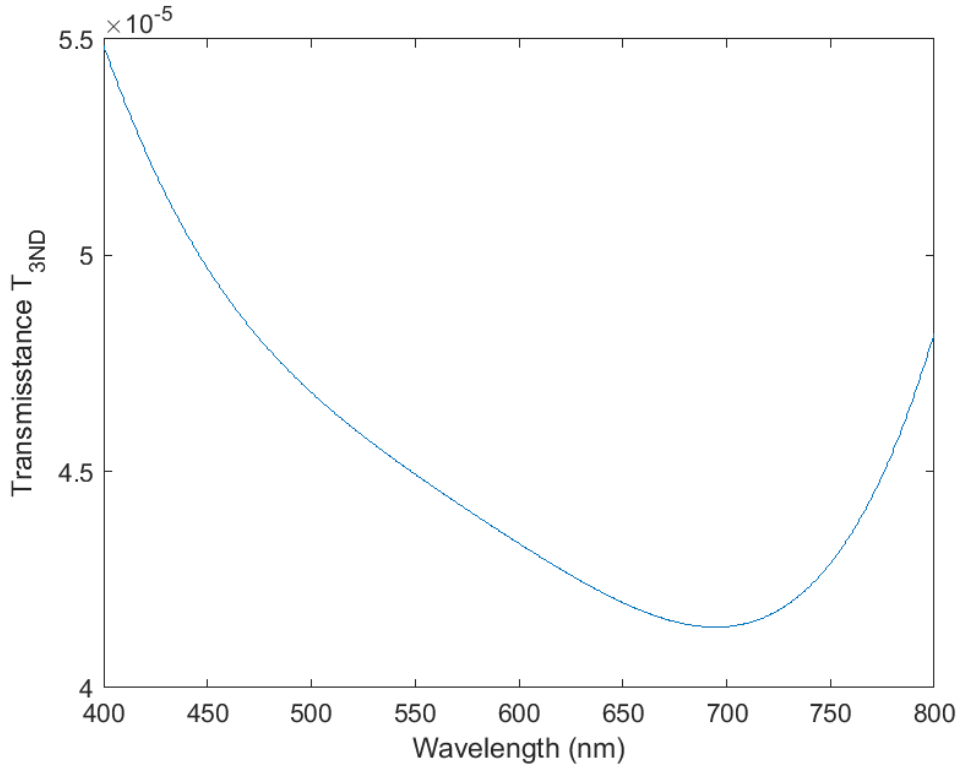


Figure 2. Transmittance of the combined ND filters as function of wavelength.

The calibration curve is derived using the following expression:

$$R(\lambda) = \frac{E(\lambda)}{T_d \frac{I_{\text{ADU}}(\lambda)}{\Delta t}} \quad (1)$$

where $E(\lambda)$ denotes the spectral irradiance of the calibration lamp, T_d the dome transmittance, and $I_{\text{ADU}}(\lambda)$ the measured signal (in ADU) obtained for an exposure time Δt , after correction for the dark current.

Neutral density (ND) filters were used to reduce the incoming flux and prevent detector saturation. The spectral irradiance of the calibration lamp, $E_{\text{lamp}}(\lambda)$, corresponds to the value measured at the B.RCLab at 50 cm distance from the source, corrected for both the spectral attenuation of the neutral filters, $T_{\text{ND}}(\lambda)$, and the geometrical dilution factor due to the lamp–instrument distance (inverse square law):

$$E(\lambda) = E_{\text{lamp}}(\lambda) \times T_{\text{ND}}(\lambda) \times \left(\frac{50}{99}\right)^2 \quad (2)$$

3.2 Grating 1

In February 2024, Grating 1 was calibrated. The camera and spectrograph parameters were identical to those described in Section 2. A range of exposure times was used during the calibration procedure. Three ND filters with attenuation factors of 8, 32 and 100 were stacked together in the optical path to reduce the incoming flux and prevent detector saturation. The ND32 filter was slightly tilted to avoid appearance of interference fringes in the observed spectra. The transmittance of the combined ND filter assembly, T_{3ND} , was subsequently characterized in the B.RCLab and is shown in Fig. 2.

The spectral irradiance of the calibration lamp was obtained using equation 2 with $E_{lamp}(\lambda) = E_{8A}$ and $T_{ND}(\lambda) = T_{3ND}$. An example of the recorded signal obtained with FEL Lamp 1 operated at 8 A for various exposure times is shown in Fig. 3.

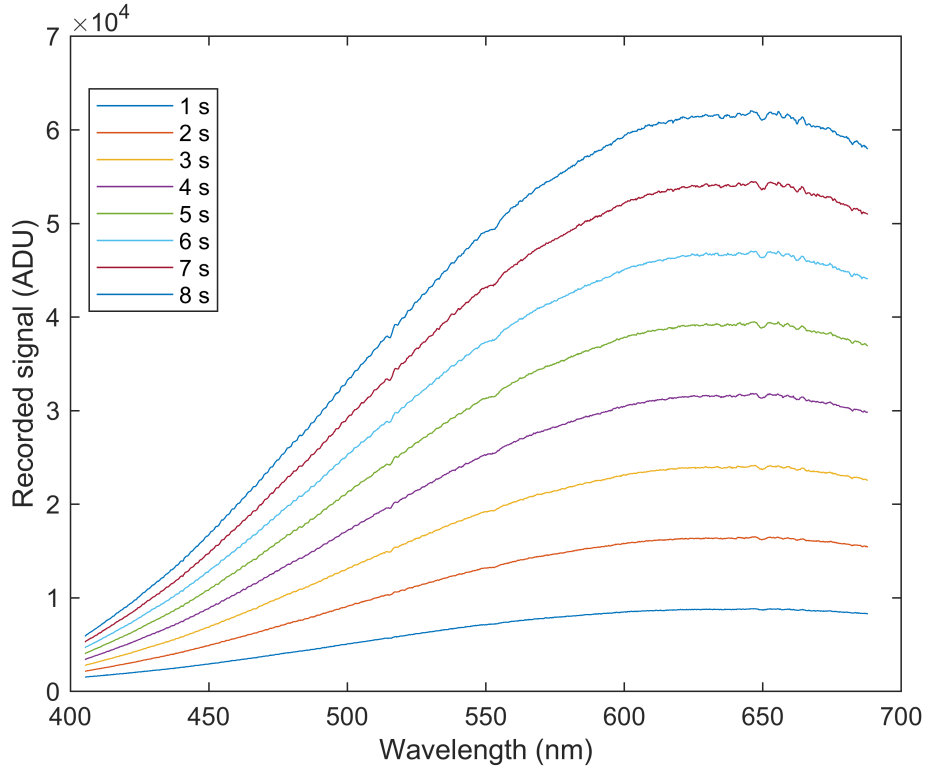


Figure 3. Recorded signal from FEL Lamp 1 as a function of wavelength for exposure times ranging from 1 to 8 s. Three ND filters were used to prevent detector saturation.

Figure 4 shows an example of the calibration curves obtained for FEL Lamp 1 operated at 8 A, with exposure times ranging from 1 to 8 s. The resulting curves overlap closely, demonstrating the consistency of the measurements. Similar results were obtained with FEL Lamp 2, providing confidence in the robustness of the calibration procedure.

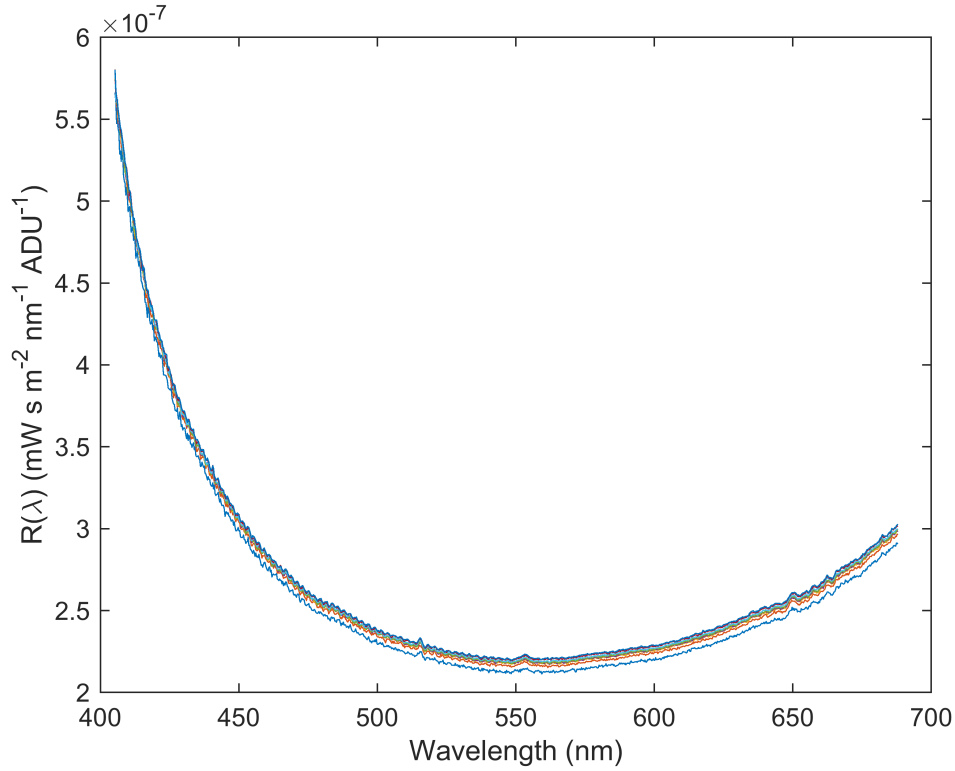


Figure 4. Calibration curves obtained for Grating 1 using FEL Lamp 1 operated at 8 A, for exposure times ranging from 1 to 8 s.

3.3 Grating 3

A second on-site radiometric calibration campaign was carried out in October 2024 to characterize Grating 3. Owing to its higher spectral dispersion, the optical configuration used for Grating 1 did not provide sufficient flux when the three-filter ND assembly was inserted. The calibration setup was therefore modified by replacing the combined ND filters with a single ND200 filter. Its wavelength-dependent transmittance was characterized independently at the B.RCLab and is shown in Figure 5.

The same FEL Lamp 2 was used for the calibration. During the campaign, however, the power supply entered safe mode when operated at the nominal current of 8 A. The lamp was consequently operated at 7 A. To preserve traceability to its 8 A spectral-irradiance calibration, the wavelength-dependent ratio between the lamp irradiances at 7 A and 8 A, $C_{7/8}(\lambda) = E_{7A}(\lambda)/E_{8A}(\lambda)$ was measured independently at the B.RCLab. The reference spectral irradiance at 8 A was then corrected using this ratio to obtain the irradiance corresponding to the 7 A operating current. The spectral irradiance of the calibration lamp was obtained using equation 2 with $E_{\text{lamp}}(\lambda) = E_{8A} C_{7/8}(\lambda)$ and $T_{\text{ND}}(\lambda) = T_{\text{ND200}}$.

Seven spectral ranges were calibrated for Grating 3. Here, we illustrate the procedure for spectral range 1, covering approximately 407.6–447.5 nm and centered on the N_2^+ first negative emission near 427.8 nm. Calibration curves were independently

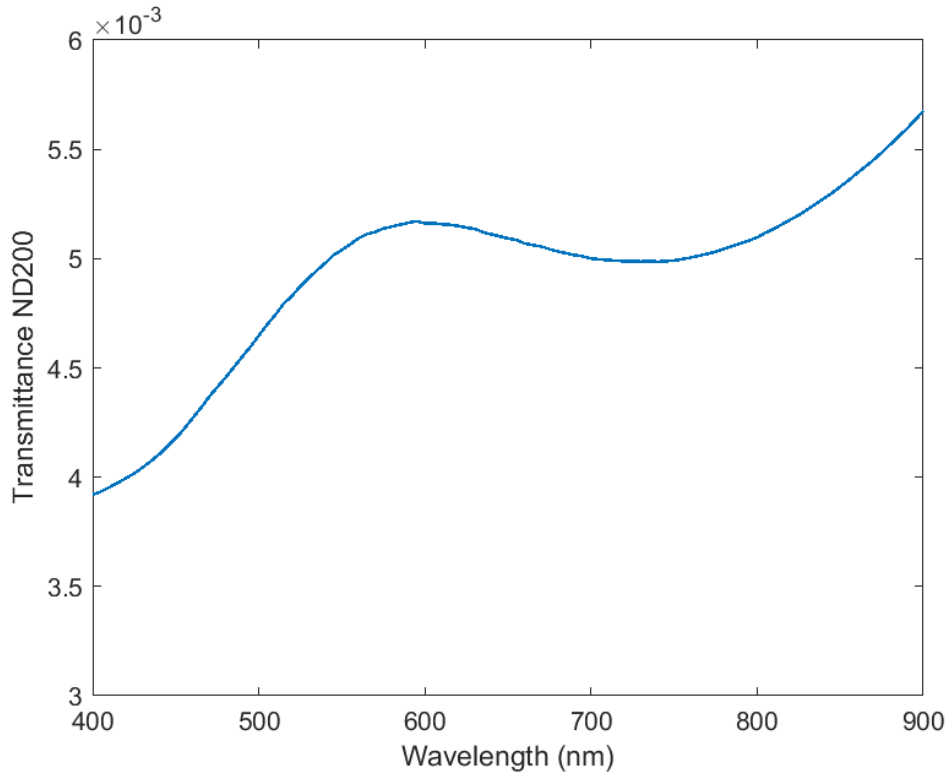


Figure 5. Measured wavelength-dependent transmittance of the ND200 filter used during the radiometric calibration of Grating 3.

135 derived from exposures of 1, 1.5, 2, 4, and 8 s. As shown in Figure 6, the five curves agree closely over the complete spectral range, demonstrating both the linearity of the detector response over these exposure times and the consistency of the calibration procedure.

3.4 Conversion to absolute spectral brightness (Rayleighs)

Using the radiometric response curve derived for the corresponding grating and spectral range, raw detector counts are first
 140 converted into spectral radiant exposure in $\text{W s m}^{-2} \text{nm}^{-1}$, i.e. the time-integrated spectral irradiance at the detector. The calibration accounts for the throughput of the telescope, fiber injection, slit, spectrograph optics, and detector response. The acrylic dome, which was not present during the calibration measurements, is accounted for separately through its transmittance T_d . Losses associated with the finite fiber-slit coupling are thus included in the instrumental response and are not corrected separately.

145 The spectra are converted to spectral irradiance in $\text{W m}^{-2} \text{nm}^{-1}$ by dividing by the 30 s exposure time, and then to spectral photon irradiance using $E_\gamma = hc/\lambda$. To convert this quantity to Rayleighs (R), the auroral emission is assumed to be spatially

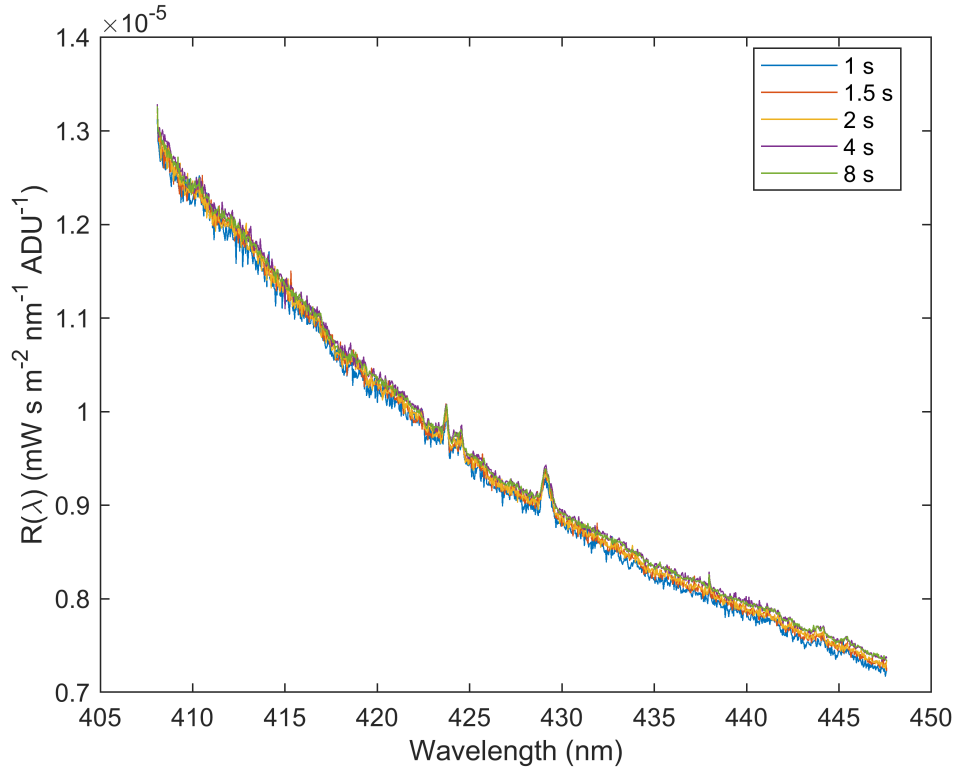


Figure 6. Calibration curves obtained for Grating 3 using FEL Lamp 2 operated at 7 A, for exposure times ranging from 1 to 8 s.

uniform over the ASIS field of view, approximated as a circular cone with a full opening angle $\alpha = 4^\circ$. The corresponding solid angle is $\Omega = 2\pi(1 - \cos \frac{\alpha}{2})$. The spectral brightness is therefore

$$I_R(\lambda) = \Phi_\lambda \frac{4\pi}{10^{10}\Omega}, \quad (3)$$

150 where Φ_λ is the spectral photon irradiance in photons $\text{s}^{-1} \text{m}^{-2} \text{nm}^{-1}$, and $I_R(\lambda)$ is the spectral radiance expressed in Rnm^{-1} . This approximation is appropriate for diffuse auroral emissions and yields a field-of-view-averaged spectral brightness otherwise.

4 Wavelength calibration

4.1 Grating 1

155 Wavelength calibration was performed using two spectral calibration lamps from Ocean Optics, both equipped with SMA connectors for direct coupling to the optical fiber. The first lamp (Hg-1) is a mercury–argon source providing strong emission

lines in the blue region of the visible spectrum. The second lamp (Ne-1) is a neon source optimized for the red part of the visible spectrum, particularly in the [540–754] nm range.

First, the wavelength range used for observations, [405–687] nm, was considered. More than 30 emission lines were identified using reference data from the National Institute of Standards and Technology (NIST). A second-order polynomial fit was then applied, yielding the following relationship between wavelength λ and pixel number p :

$$\lambda = 405.033 + 0.278 p - 1.679 \times 10^{-6} p^2 \quad (4)$$

The result is shown in Figure 7, where the measured line positions are displayed as dots and the polynomial fit as the red curve. For comparison, the automatic calibration provided by the spectrograph dashboard is also shown. This built-in calibration is obtained by interactively selecting emission-line peaks and entering their corresponding wavelengths. The two calibration curves are nearly parallel. The small offset (=7 nm) between them likely arises from minor mechanical variations that shift the spectrum on the detector, for example due to slight misalignment of the camera or the grating turret.

Another wavelength range was investigated, extending further into the red part of the spectrum: [519–800] nm, with a central wavelength $\lambda_c = 660.27$ nm. The following second-order polynomial fit was found:

$$\lambda = 511.830 + 0.277 p - 3.248 \times 10^{-6} p^2 \quad (5)$$

The corresponding wavelength calibration curve is shown in Figure 8, exhibiting the same constant offset as previously observed. The fact that the calibration curves remain parallel over both wavelength ranges supports the validity and consistency of the calibration procedure.

4.2 Grating 3

Grating 3 with $1800 \text{ lines mm}^{-1}$ provides higher-resolution spectra to resolve specific auroral emission lines during dedicated campaigns. Its spectral dispersion is $\frac{d\lambda}{dp} \sim 0.05 \text{ nm pixel}^{-1}$.

During the wavelength calibration campaign, seven spectral ranges were selected including the following emission lines: 427.8 nm ($\text{N}_2^+ \text{ 1NG}$), 510.0 nm (region with several bands of $\text{N}_2 \text{ 2P}$), 557.7 nm ($\text{O}(^1S \rightarrow ^1D)$), 630.0 nm ($\text{O}(^1D \rightarrow ^3P_2)$), 636.4 nm ($\text{O}(^1D \rightarrow ^3P_1)$), 656.3 nm (H_α), 732.0 nm (doublet $\text{O}^+ (^2D \rightarrow ^2P)$), and 777.4 nm (multiplet $\text{O}(3p^5P \rightarrow 3s^5S^o)$).

Because each spectral window spans only about 40 nm, relatively few calibration lines are available within a single exposure. To increase the number of identifiable lamp lines, the exposure time was intentionally increased so that weaker emission lines became detectable, while the brightest lines were allowed to saturate. This strategy typically provided more than ten emission lines for the wavelength calibration of each spectral range.

As an illustration, for the spectral range 1 (centred on the $\text{N}_2^+ \text{ 1NG}$ emission at 427.8 nm), the following second-order polynomial fit was found:

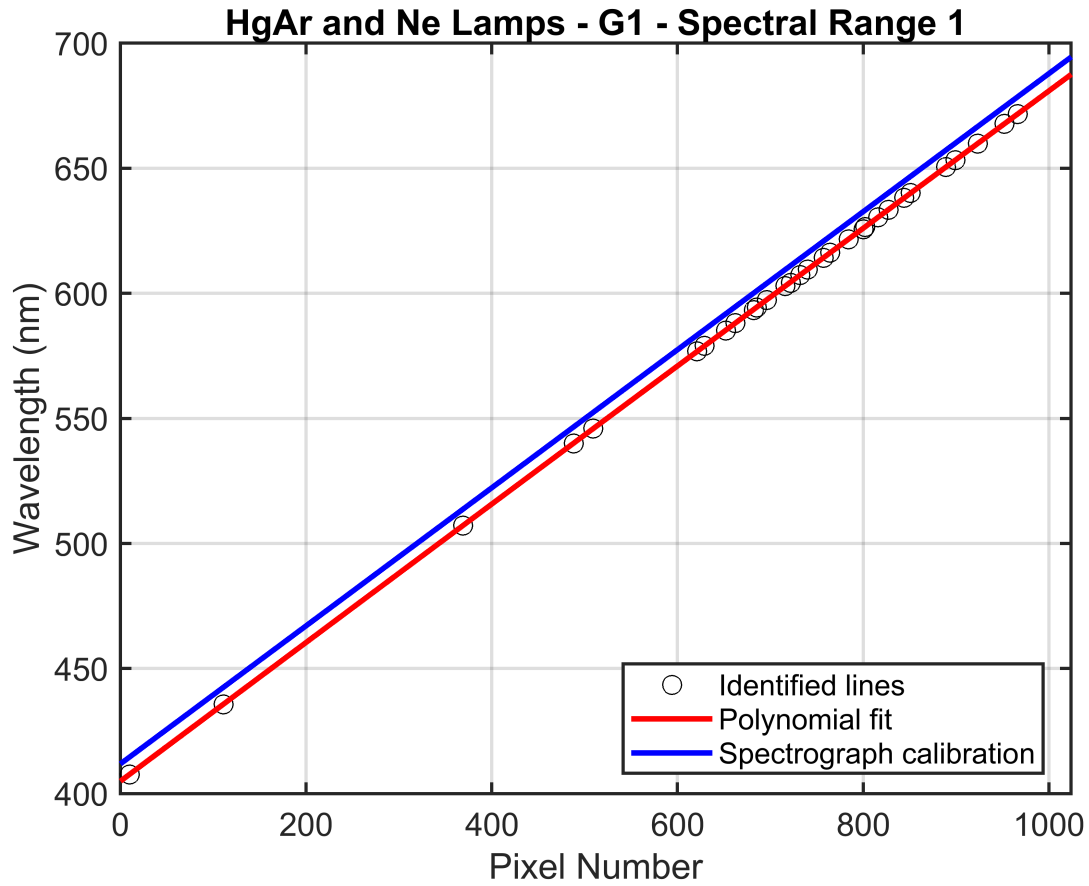


Figure 7. Wavelength calibration curves in the range [405–687] nm. The black dots represent manually identified emission lines from the HG-1 and Ne-1 spectral lamps. The red curve shows the second-order polynomial fit derived from these measurements. The blue curve corresponds to the linear dispersion relation automatically provided by the SR-303i spectrograph control software, based on the factory calibration.

$$\lambda = 408.046 + 0.040 p - 1.354 \times 10^{-6} p^2 \quad (6)$$

The corresponding wavelength calibration curve is shown in Figure 9, exhibiting a different constant offset than previously observed. The change in the constant offset simply reflects the different optical configuration associated with Grating 3.

190 As an example of ASIS performance in the blue spectral range, Figure 10 shows a radiometrically calibrated auroral spectrum between 415 and 440 nm. The spectrum was obtained by averaging 20 consecutive 60 s exposures, corresponding to a total integration time of 20 min. After dark subtraction and radiometric calibration, the N_2^+ first negative (1NG) (0,1) band at 427.8 nm is clearly detected, together with the weaker (1,2) and (2,3) bands at 423.6 and 419.9 nm, respectively.

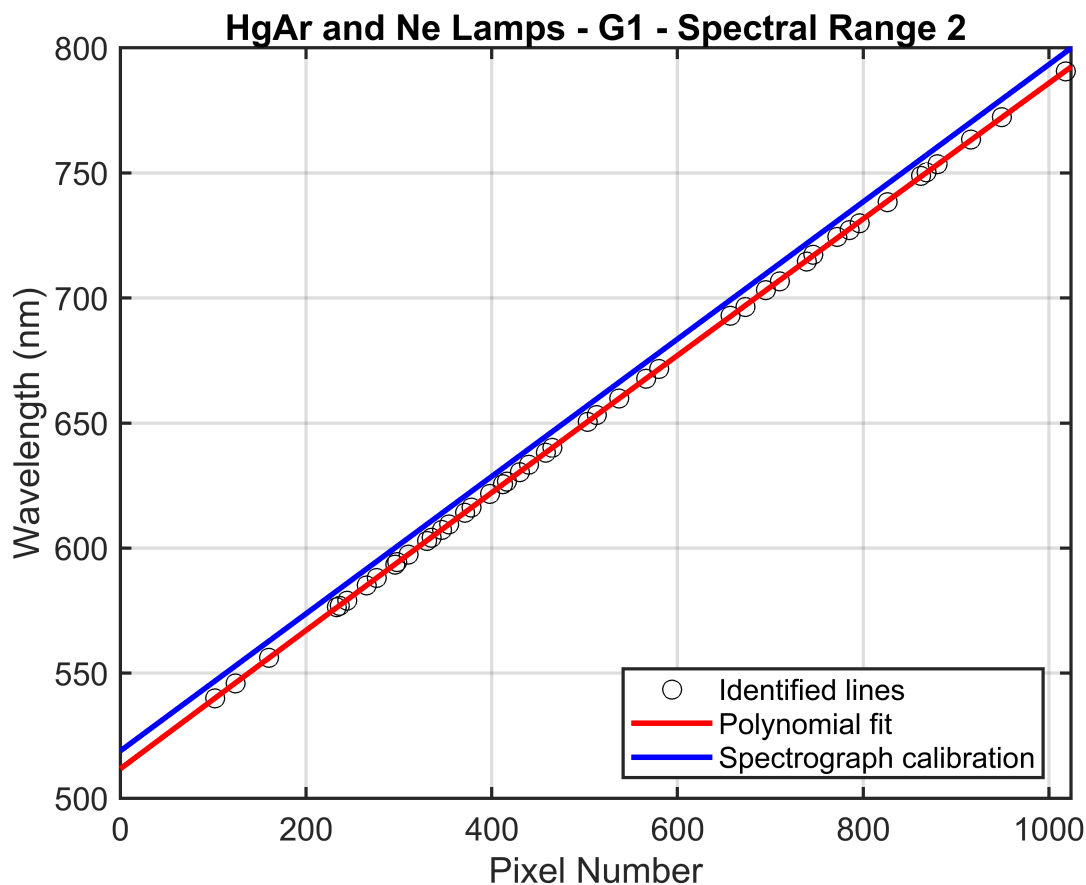


Figure 8. Wavelength calibration curves in the range [519–800] nm using the HG-1 and Ne-1 spectral lamps. The dots and red curve correspond to a polynomial fit of the manually identified emission lines while the blue curve is a linear variation provided automatically by the dashboard controlling the SR-303i spectrograph and corresponding to a factory calibration.

5 Examples of data and applications

195 5.1 Geomagnetic Storms and Substorms

During periods of enhanced geomagnetic activity, including geomagnetic storms and substorms, ASIS records a broad range of auroral atomic lines and molecular bands. These intervals provide useful test cases for assessing the spectral capabilities of the instrument, because both the main auroral emissions and weaker spectral features can be detected within the same observations.

An example is shown in Figure 11. The spectrum exhibits clear emissions from the first negative band system of N_2^+ (1NG), as well as from the first positive band system of N_2 (1PG). In addition to the dominant auroral emissions, weaker spectral features are also visible, including the [N I] emission near 520 nm and the [N II] emission near 500 nm. Such spectra provide a

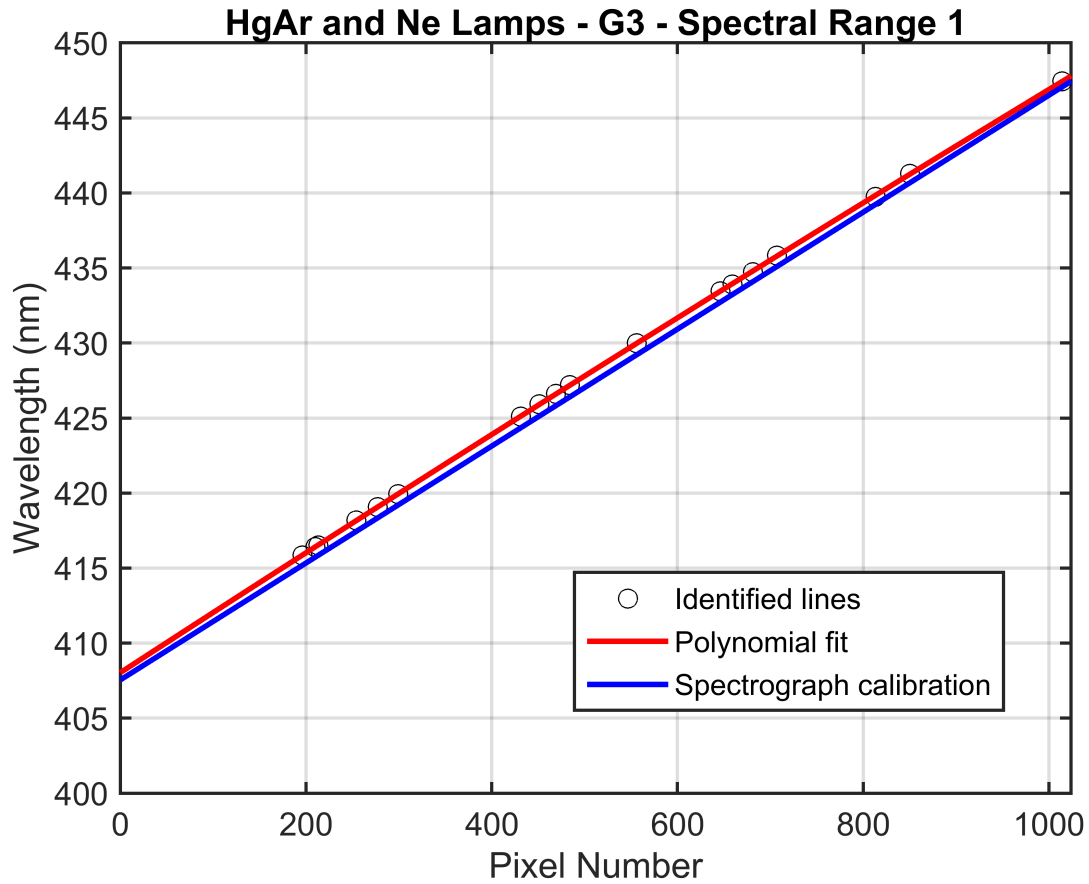


Figure 9. Wavelength calibration curves in the range [407.6–447.5] nm. The black dots represent manually identified emission lines from the HG-1 and Ne-1 spectral lamps. The red curve shows the second-order polynomial fit derived from these measurements. The blue curve corresponds to the linear dispersion relation automatically provided by the SR-303i spectrograph control software, based on the factory calibration.

direct view of the relative contributions of atomic oxygen, molecular nitrogen, ionized molecular nitrogen, and atomic nitrogen emissions during disturbed geomagnetic conditions.

ASIS is also useful as a ground-based spectroscopic support instrument in broader multi-instrument studies. A recent example is given by Nanjo et al. (2026), where ASIS observations were used together with all-sky imaging, narrow-band optical cameras, a spectral riometer, ground magnetometer measurements, high-speed imaging, and Swarm satellite observations to investigate fragmented aurora-like emissions and picket-fence structures near the poleward edge of the auroral oval. In such studies, imaging data provide the morphology, motion, and spatial context of the aurora, while ASIS provides the spectral identification of the emitting species and their relative intensities.

The continuous ASIS observations also provide calibrated time series of the main auroral emissions (see Figure 12). These time series make it possible to follow the temporal evolution of the N_2^+ 427.8 nm band, the $O(^1S)$ 557.7 nm line, the $O(^1D)$

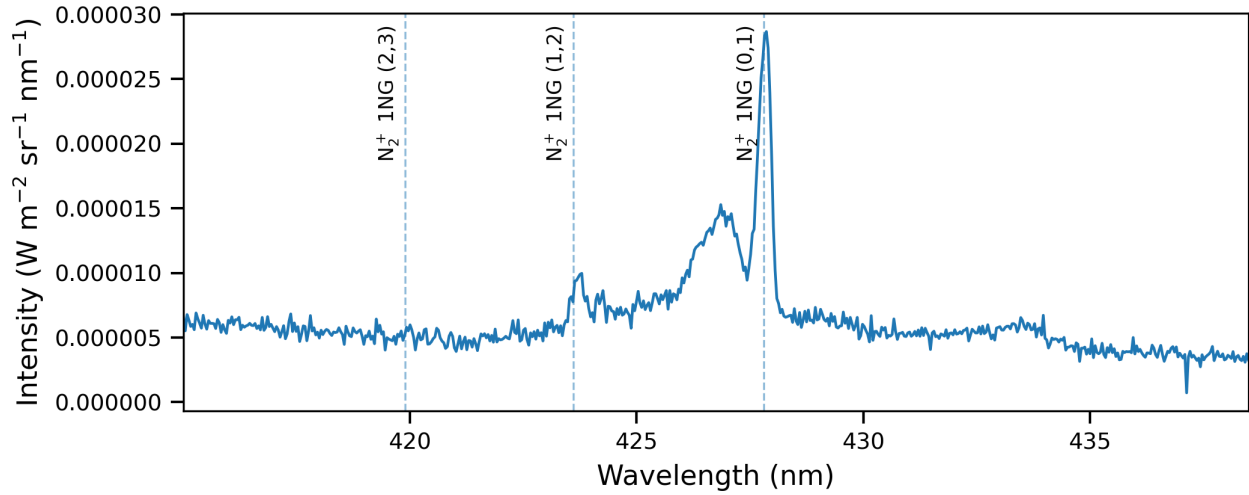


Figure 10. Radiometrically calibrated ASIS spectrum obtained with Grating 3, showing the N_2^+ first negative band heads at 419.9, 423.6, and 427.8 nm

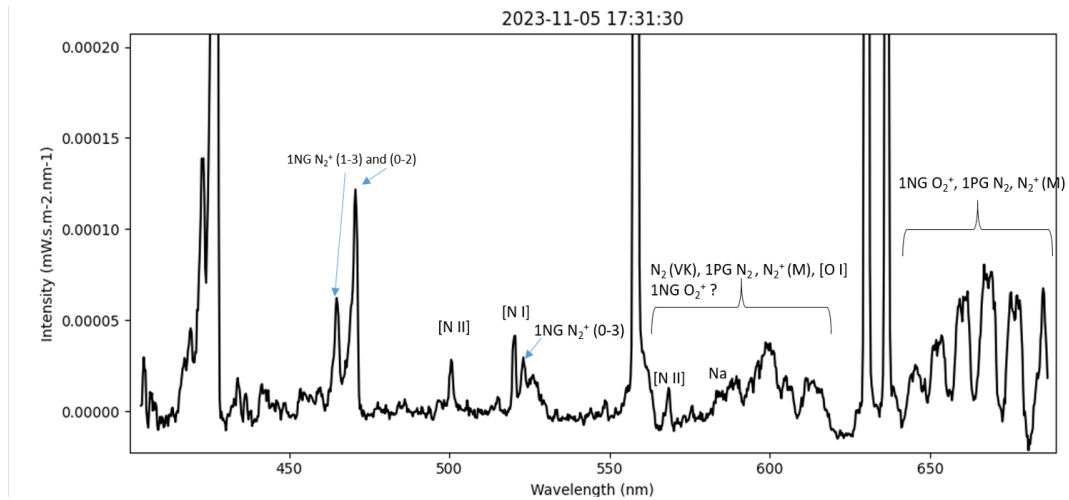


Figure 11. Example of an ASIS spectrum recorded during enhanced geomagnetic activity on the 5th of November 2023.

630.0 and 636.4 nm lines. This temporal information is essential for identifying stable intervals where line-ratio diagnostics can be interpreted physically, and for distinguishing rapidly evolving substorm structures from quieter arcs, diffuse aurora, or mixed precipitation regimes.

Line-intensity ratios can be used as proxies for the characteristic energy of precipitating auroral electrons. In particular, the ratio between red oxygen emissions at 630 nm and blue N_2^+ emissions provides a useful diagnostic of electron precipitation energy, as illustrated in Figure 12. In this work, the red-to-blue ratio is computed from calibrated and spectrally integrated emissions, rather than from peak intensities alone.

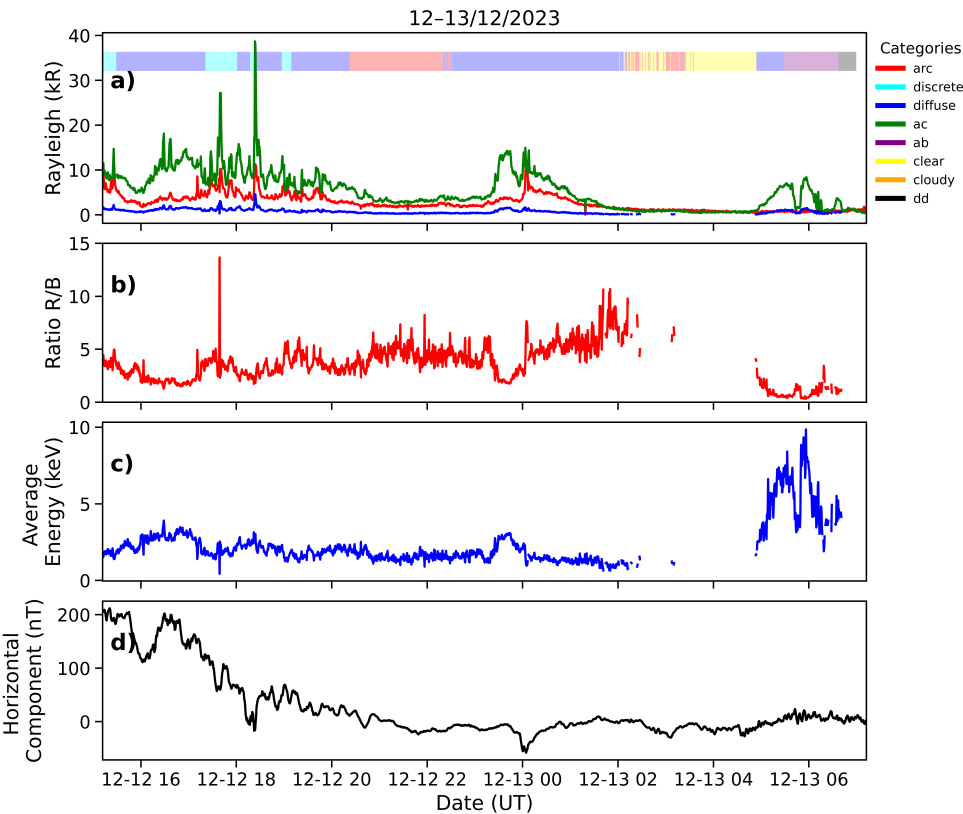


Figure 12. Results from ASIS for 12-13 December 2023. Panel a): green (557.7 nm), red-doublet (630/636 nm), and blue (427.8 nm) intensities, together with the AI-based morphology classification from Nanjo et al. (2022); Panel b): ratio between the 630 nm line emission and the 427.8 nm. Panel c): average energy using the look-up table from Adachi et al. (2017) in blue. Panel d): magnetic disturbance horizontal component from Tromsø magnetic observatory.

220 The physical interpretation of this ratio relies on electron transport models. The observed ratios can be compared with look-up tables derived from models such as Transsolo (Barthelemy et al., 2025), using up to 32 streams, or with earlier two-stream

calculations such as those of Ono (1993) and Adachi et al. (2017). These models provide the expected auroral emission ratios as a function of the characteristic energy of the precipitating electrons.

The auroral classifications used for Figure 12 follow the machine-learning-based classification results of Nanjo et al. (2022) for the Skibotn all-sky camera. This classification provides an independent morphological context for separating diffuse, pulsating, arc-like, and disturbed auroral conditions. A detailed application of this approach to pulsating aurora and the morning-sector increase of characteristic electron energy is discussed in Cessateur et al. (2026).

A complementary reconstruction approach, based on fitting ASIS spectra with synthetic spectra generated by the Transsolo electron transport model, is currently being developed to retrieve both the total energy flux and the mean energy of the precipitating electron distribution from monitoring-mode spectroscopic observations.

5.3 Proton Aurora

ASIS also regularly detects spectral signatures associated with proton aurora. These signatures include Balmer emissions, in particular $H\alpha$ and $H\beta$ as shown in Figure 13.

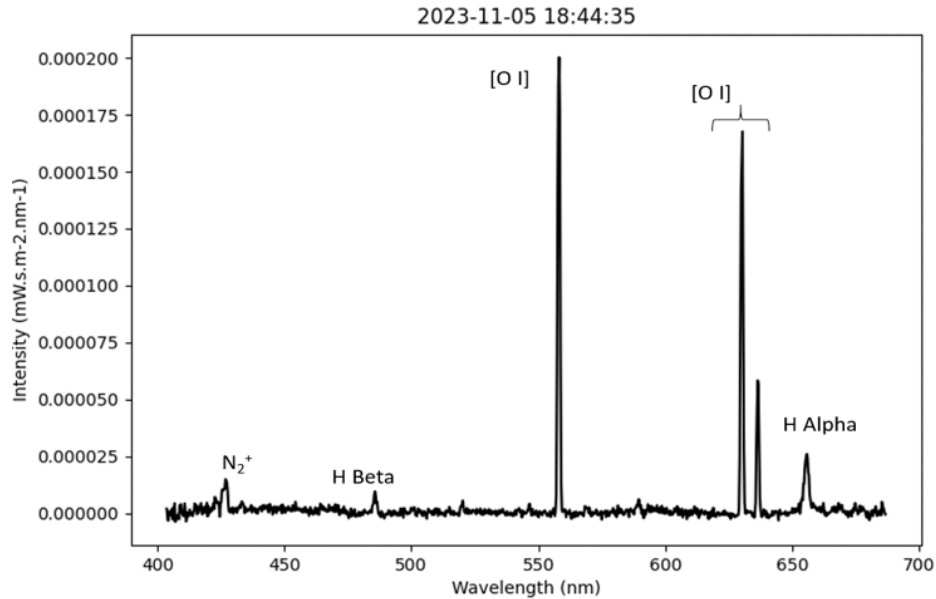


Figure 13. Example of an ASIS spectrum showing Balmer emissions associated with proton aurora on 5 November 2023. The $H\beta$ and $H\alpha$ lines are detected together with the main electron-auroral emissions, including the N_2^+ band near 427.8 nm, the $O(^1S)$ green line at 557.7 nm, and the $O(^1D)$ red lines at 630.0 and 636.4 nm. The simultaneous presence of Balmer and oxygen/nitrogen emissions suggests a mixed proton and electron precipitation regime.

Proton aurora is produced when precipitating magnetospheric protons, typically with energies in the keV to tens-of-keV range, interact with the upper atmosphere. Charge-exchange reactions can produce fast neutral hydrogen atoms, which may

subsequently radiate through the Balmer series. Because these neutral hydrogen atoms are no longer constrained by the geomagnetic field, proton aurora can have spatial and spectral characteristics that differ from purely electron-driven aurora (Galand and Chakrabarti, 2006).

6 Conclusions

240 ASIS is a ground-based auroral spectrograph designed for continuous monitoring of visible auroral emissions at Skibotn Observatory. In its standard configuration, Grating 1 provides spectral coverage over approximately 405-687 nm with a spectral resolution of about 1.2 nm, while Grating 3 provides higher spectral dispersion for dedicated observations of selected auroral emission features.

245 The instrument has been characterized through both wavelength and radiometric calibration campaigns. Absolute radiometric response curves were obtained using calibrated FEL lamps, with grating-specific calibration configurations adapted to the different optical throughput and spectral dispersion. The consistency of the response obtained for different exposure times demonstrates the stability and linearity of the calibration procedure. Together with the wavelength calibration, these measurements allow ASIS spectra to be expressed in absolute spectral brightness units and therefore used for quantitative auroral studies.

250 The observations presented here illustrate several scientific applications of ASIS. The instrument resolves the main atomic and molecular auroral emissions during disturbed geomagnetic conditions, provides calibrated line intensities and ratios that can be used to constrain the characteristic energy of precipitating electrons, and detects Balmer emissions associated with proton precipitation. Its continuous operation also makes ASIS well suited for coordinated studies with all-sky imaging, radar, magnetometer, and satellite observations. Further developments based on comparisons with synthetic spectra from electron transport models will extend these measurements towards the quantitative retrieval of precipitating particle energy fluxes and characteristic energies.

Code and data availability. The MATLAB codes and associated data used to derive the response curves and generate the figures presented in this study are available at https://asis.aeronomie.be/UploadDir/Data_and_Codes_for_Article_ASIS.zip.

Author contributions. Hervé Lamy coordinated the study, contributed to the installation and calibration of the ASIS instrument, developed the MATLAB analysis codes, and wrote the manuscript. Gaël Cessateur contributed to the installation of ASIS and to the preparation of the manuscript. David Bolsée contributed to the radiometric calibration of the instrument and performed the laboratory characterization of the calibration sources and neutral-density filters. He also contributed to the preparation of the manuscript. Mathieu Barthélemy contributed to the installation of the instrument and reviewed the manuscript. Magnar Gullikstad Johnsen provided access to the Skibotn Observatory, supported the long-term operation of ASIS, and reviewed the manuscript. All authors discussed the results and approved the final version of the manuscript.

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

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