



NORVIS: a portable broadband imaging spectrograph for auroral observations

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Abstract. We present NORVIS (NORdlys Versatile Imaging Spectrograph), a portable broadband imaging spectrograph developed for ground-based auroral observations. Based on the Star'Ex optical concept, NORVIS is optimized for auroral emissions and covers approximately 380-860 nm in a single acquisition at a moderate spectral resolution of 1.2 nm FWHM. The instrument combines auroral spectroscopy, wide-field context imaging, field operation, automated spectral reduction, and centralized data archiving within a researcher-citizen science framework. First observations were obtained during a campaign at Skibotn Observatory, Norway, in February 2026, during which approximately 1200 spectra were acquired and reduced over three observing nights, with typical exposure times of 30 s. These observations demonstrate the simultaneous detection of key auroral emissions, including the N₂⁺ 1NG bands at 391.4 and 427.8 nm and the [O I] emissions at 557.7 and 630.0/636.4 nm, while also providing access to the H α region and to O I emissions at 777.4 and 844.6 nm. Representative observations illustrate the potential of NORVIS for emission-ratio diagnostics and geometry-aware interpretation of auroral structures. NORVIS is intended to form the basis of a distributed observing network, with coordinated deployments planned in Kiruna, Skibotn, Svalbard, and northern Finland, followed by permanent installations at Kiruna, Skibotn, the Kjell Henriksen Observatory in Svalbard, and Nyrölä.

1 Introduction

Discrete and diffuse auroral emissions arise from a combination of excitation, ionization, and relaxation processes. These processes may be driven by precipitating particles, while collisional excitation associated with ion-neutral drift can also contribute, particularly to diffuse emissions. The resulting emissions encode information on the energy distribution of precipitating par-



ticles, auroral electric fields, and the state of the upper atmosphere. Optical spectroscopy provides access to this information through the simultaneous observation of multiple atomic and molecular emissions, whose relative intensities, spectral structure, and temporal response reflect different aspects of the underlying physical processes (Chamberlain, 1961; Vallance Jones, 1974; Rees, 1989).

A key aspect of auroral diagnostics is that different emissions probe different excitation regimes. Some emissions are associated with prompt processes and respond rapidly to particle precipitation, while others involve longer-lived states and are influenced by transport, quenching, and chemical relaxation. As a result, combining spectral features with different characteristic timescales provides complementary constraints on particle energy and atmospheric conditions, but also introduces additional complexity in the interpretation of integrated line-of-sight measurements.

Moderate-resolution spectrographs, typically around 1.2 nm FWHM, such as the Meridian Imaging Svalbard Spectrograph (MISS) described by Herlingshaw et al. (2025) and the Auroral Structure and Imaging Spectrograph (ASIS) introduced by Cessateur et al. (2026), are optimized to measure relative intensities across selected spectral ranges, enabling the use of established emission ratios to infer particle precipitation characteristics. These instruments provide robust and well-calibrated measurements, but are generally limited in spectral coverage, restricting the number of emission systems that can be observed simultaneously. Another recent development is the hyperspectral camera for auroral imaging (HySCAI), which provides two-dimensional auroral spectral images with either 400–800 nm coverage at 2.1 nm FWHM or a 123 nm spectral window at 0.73 nm FWHM (Yoshinuma et al., 2024).

Complementary approaches have been developed to investigate auroral dynamics and thermospheric response. Coordinated optical systems, such as those deployed within the Transition Region Explorer (TReX) network, combine imaging and spectroscopic measurements to study fine-scale structures and transient phenomena (Gillies et al., 2019). At high latitudes, spectroscopic observations co-located with incoherent scatter radars enable detailed investigations of thermospheric parameters and energy deposition processes through multi-instrument analysis (Conde and Smith, 1995, 1997; Tsuda et al., 2020).

A distinct diagnostic regime is accessed by high-dispersion spectrographs, such as imaging echelle instruments including the High Throughput Imaging Echelle Spectrograph (HiTIES, Chakrabarti et al. 2001). These systems are designed to resolve the detailed shape of emission lines, enabling Doppler-based measurements of neutral temperatures, winds, and non-thermal broadening, as well as resolving the rotational structure of molecular band systems. Their strength lies in the analysis of line profiles, rather than in the simultaneous observation of a large number of emission systems over a broad spectral range.

Taken together, these approaches illustrate a fundamental trade-off in auroral spectroscopy between spectral resolution, spectral coverage, and deployability. Instruments optimized for high spectral resolution provide detailed information on line profiles but typically operate over narrow wavelength ranges. Conversely, moderate-resolution systems allow access to multiple emission features but often remain restricted in spectral coverage or require multiple configurations. In addition, most high-performance instruments are deployed at a limited number of locations, limiting their ability to capture the strong spatial variability of auroral structures. This limitation becomes particularly critical for the study of discrete aurora, where combining emissions associated with different excitation regimes, such as prompt molecular emissions and longer-lived atomic transitions,



can provide stronger constraints on particle precipitation. Achieving this requires instruments capable of broad spectral coverage within a single acquisition, while remaining sufficiently simple and well-characterized to enable distributed observations.

Recent observations of STEVE, for "Strong Thermal Emission Velocity Enhancement" (MacDonald et al., 2018; Gillies et al., 2019, 2023; Nanjo et al., 2024), continuum-like aurora (Partamies et al., 2025; Dayton-Oxland et al., 2025), fragmented aurora-like emissions (FAEs) (Dreyer et al., 2021), and picket-fence structures (Nanjo et al., 2026b) further show that broadband spectroscopy is becoming essential for distinguishing classical precipitation-driven aurora from locally generated or continuum-like optical emissions.

Recent developments in compact spectrographs have opened new perspectives toward distributed observation approaches. The Star'Ex concept¹ originally developed as a compact and reproducible astronomical spectrograph with interchangeable low- and high-resolution configurations, demonstrating that relatively simple optical designs can achieve significant spectral performance. Early adaptations of Star'Ex have also confirmed its ability to detect auroral emissions. These developments have fostered the emergence of collaborative frameworks involving both professional and amateur communities. In auroral research, such coordinated international initiatives remain relatively recent (e.g., the Auroral Research Coordination: Towards Internationalised Citizen Science (ARCTICS; <https://collab.issibern.ch/arctics/>, last access: 27 August 2026) working group supported by the International Space Science Institute (ISSI) in Bern, who produced an Aurora Handbook and Field Guide for Citizen Science (Herlingshaw et al., 2024)) and highlight the potential of citizen science to expand the spatial coverage of spectroscopic observations. However, citizen-science auroral observations are still dominated by commercial RGB cameras with broad and overlapping spectral responses. These cameras provide valuable colour and morphological information but do not provide a resolved emission spectrum (Nanjo et al., 2026a). Although compact spectrographs such as Star'Ex can provide spectral information, their existing configurations were not optimized for diffuse auroral emissions in terms of signal-to-noise ratio (SNR), and also required multiple instrumental settings to cover the visible and near-infrared spectral range.

In this context, we introduce the NORVIS ("NORdlys Versatile Imaging Spectrograph"), a compact spectrograph designed to address these limitations by combining broad spectral coverage (380-860 nm), moderate spectral resolution, and a reproducible system architecture. By enabling the simultaneous observation of multiple emission systems across different excitation regimes, NORVIS extends the accessible diagnostic space beyond that of existing instruments, while remaining compatible with distributed and community-driven observational strategies. The present paper focuses on the instrumental design and initial validation of NORVIS. First observations demonstrate its ability to detect key auroral emissions and to capture spatial and temporal variability within auroral structures. The scientific exploitation of this instrument, including quantitative interpretation and coordinated multi-site observations, will be addressed in future work.

¹<https://solex.astrosurf.com/sol-ex-stars-en.html>

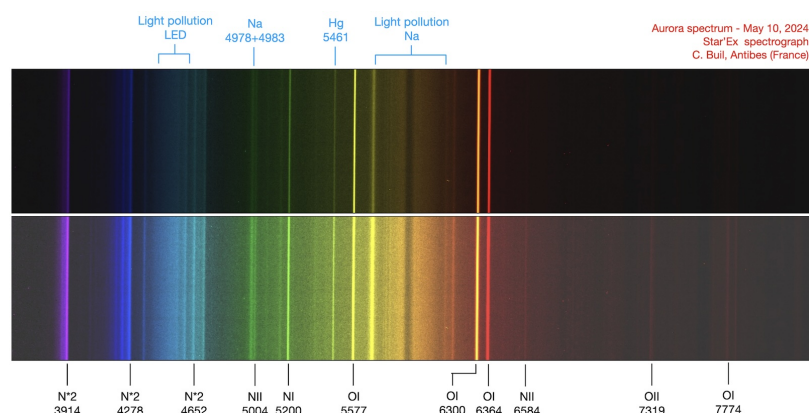


Figure 1. First auroral spectrum obtained with a Star'Ex spectrograph with 30 min exposure time, from Antibes, France, (43.58° N, 7.12° E), during the 10 May 2024 geomagnetic storm. The lower panel shows the same spectrum after adjustment of the brightness and intensity scale to reveal weaker emission lines that are not readily visible in the original image.

2 Star'Ex as a precursor for compact auroral spectroscopy

2.1 First auroral light

The Star'Ex spectrograph was originally developed as a versatile instrument for astronomical spectroscopy, providing both low- and high-resolution configurations. Its optical design enables access to a broad spectral domain, typically extending from the near-ultraviolet to the near-infrared (380-860 nm), through the use of different instrumental setups. In the context of auroral spectroscopy, this capability is particularly relevant, as it allows multiple emission systems to be observed across the visible range. Star'Ex therefore provides a suitable platform for exploring auroral spectra using compact and relatively cheap instrumentation.

The first auroral spectrum obtained with a Star'Ex spectrograph was recorded in Antibes, France, at mid-latitudes (43.58° N, 7.12° E) during the geomagnetic storm of 10 May 2024, using the low-resolution setup coupled with an Askar PHQ107 refractor (Fig. 1). Despite the long exposure time (30 min), this observation revealed several key auroral emission features. In particular, the atomic oxygen lines at 630.0 and 636.4 nm are prominently detected, together with the 557.7 nm line. The relative dominance of the red emissions is consistent with mid-latitude observations, although red emissions were particularly prominent during that specific storm (Grandin et al., 2024). Molecular nitrogen ion emissions (N_2^+) are also clearly visible, notably the bands at 391.4 nm and 427.8 nm, as well as features around 470.9 nm. In addition, near-infrared emissions, such as the oxygen line at 777.4 nm, can be identified.

2.2 Observations under high latitude auroral conditions (October 2025)

Following these initial proof-of-feasibility observations, a series of measurements was conducted under auroral conditions during a campaign in October 2025 at the Skibotn Observatory, Norway (69.35°N, 20.36°E). This location, situated within

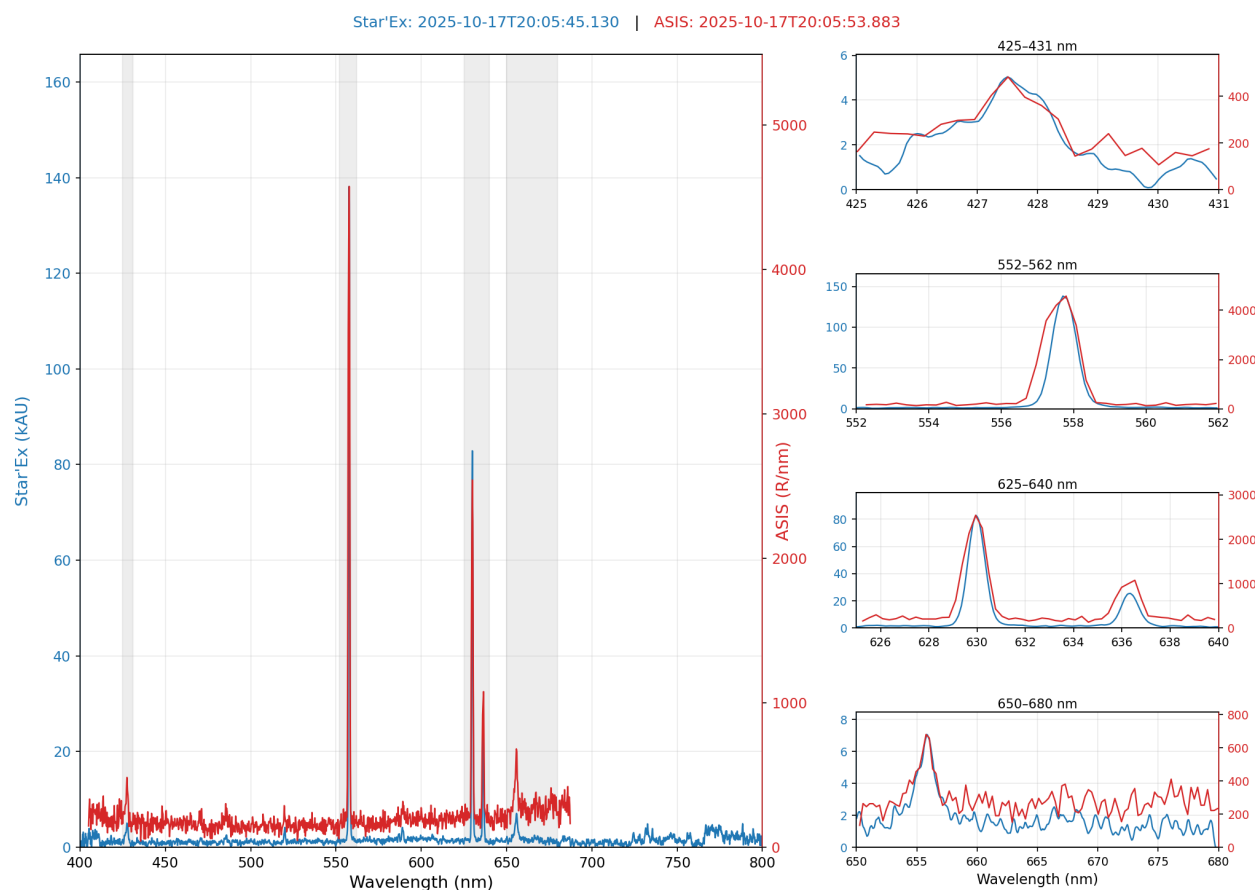


Figure 2. Comparison between Star'Ex (in blue) and ASIS (in red) auroral spectra obtained during the October 2025 campaign at Skibotn. Unlike ASIS, the Star'Ex spectrum is not calibrated and is given in kADU.

the auroral zone, provides favorable conditions for observing bright and dynamically evolving auroral structures. These observations were performed using Star'Ex spectrographs at the same time, enabling the acquisition of spectra over an extended wavelength range. Compared with the initial mid-latitude observations, the data obtained under auroral conditions exhibit a higher signal level and richer spectral content.

Despite overcast skies, a wide variety of auroral emissions was detected, including atomic oxygen lines, hydrogen Balmer emissions, and molecular nitrogen band systems, as shown in Fig. 2. The figure also provides a direct comparison with the calibrated ASIS instrument (Cessateur et al., 2026), permanently installed at the Skibotn Observatory. Both instruments have similar spectral resolutions of about 1.2 nm FWHM and comparable SNRs. The wavelength calibration of the Star'Ex data was performed using the ASIS spectral scale as a reference considering the main spectral emission lines in common. The



Star'Ex spectrum shown here combines measurements from two spectral configurations, producing a spectrum extending approximately from 400 to 750 nm.

These observations confirm that Star'Ex-type instruments can provide detailed auroral spectra under favorable conditions and demonstrate their potential for multi-diagnostic analysis. However, achieving such spectral coverage still requires the combination of multiple instrument configurations, which complicates operations and limits the consistency of the acquired datasets.

Moreover, the optical design of Star'Ex was not originally optimized for diffuse sources such as auroral emissions, leaving room for improvement in throughput, field configuration, and operational stability. This motivated the development of a dedicated spectrograph covering a broad auroral spectral range, from the N_2^+ (0,0) band at 391.4 nm to the oxygen emission at 844.6 nm, while preserving sufficient temporal resolution for the study of auroral variability.

3 The NORVIS spectrograph

3.1 Optical configuration

The instrument follows the classical architecture of a slit spectrograph, comprising an entrance slit, a collimator objective, a diffraction grating, and a camera objective that forms the dispersed spectrum on an array detector. Figure 3 presents a three-dimensional view of the complete optical assembly. The overall optical design was developed to maintain a compact instrument while meeting the requirements for spectral resolution, wavelength coverage, and field flatness.

The entrance-slit assembly consists of a 2 mm-thick fused-silica plate. Its first surface is treated with an antireflection coating, while its second surface is coated with a thin opaque chromium layer in which four 4 mm-long slits are etched using photolithography. The selectable slit widths are 14, 20, 26, and 32 μm , allowing the spectral resolution and optical throughput to be adapted to different observing applications. A slit width of 20 μm is nominally used for auroral observations, ensuring the desired spectral resolution, of about 1.2 nm as discussed in Sect. 3.4.

The collimator and camera objectives are identical achromatic doublets, each 20 mm in diameter and with a focal length of 50 mm. Their optical prescriptions use selected optical glasses and were optimized in Zemax together with the diffraction-grating geometry. Using the same optical design for the collimator and camera objectives simplifies instrument assembly and reduces manufacturing costs, which is particularly advantageous for producing multiple units.

The dispersive element is a plane, mechanically-ruled reflection grating with 300 grooves mm^{-1} and a blaze optimized for the visible spectral range. Its ruled area measures 12.7 mm $\times$ 12.7 mm.

The grating is operated at an angle of incidence of 25° and a diffraction angle of 15° , with a total beam deviation of 40° and a central wavelength of about 546 nm in the first order. The resulting anamorphic magnification ($\cos \alpha / \cos \beta \simeq 0.94$) slightly narrows the slit image in the dispersion direction.

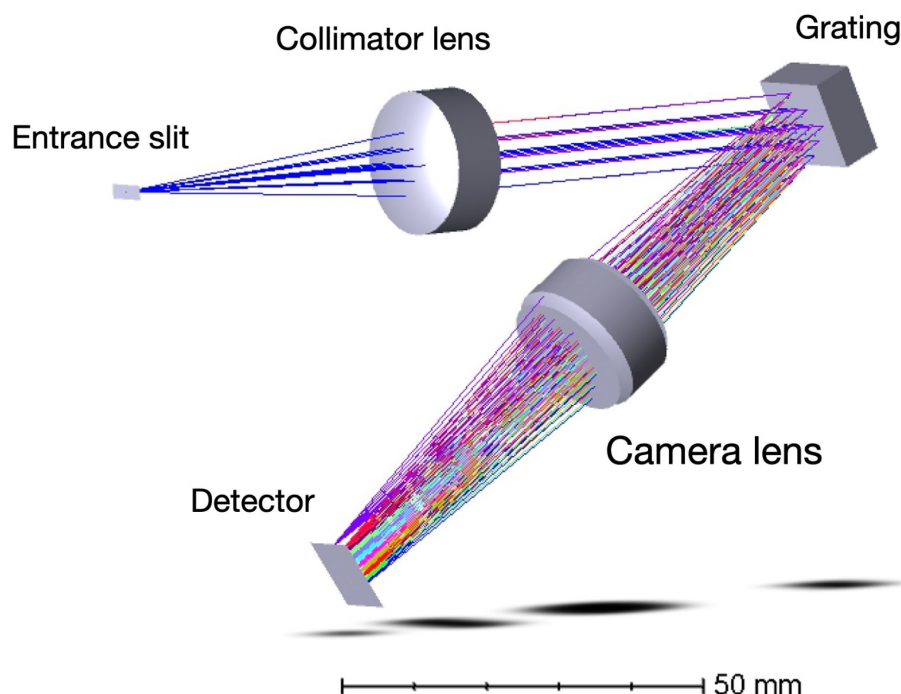


Figure 3. Optical layout of the NORVIS spectrograph, generated using Ansys Zemax OpticStudio ray-tracing software.

3.2 Entrance optics and input beam

- 140 The auroral scene is imaged by a 50 mm focal-length achromatic doublet onto the reflective entrance slit. The usable slit length is 4 mm, corresponding to an instantaneous angular field of view along the slit of approximately 4.6° . The input beam is stopped to $f/5$, corresponding to a clear aperture of 10 mm, so that the complete field sampled by the slit is accepted without vignetting. The entrance-slit plane is tilted by 15° , allowing the reflective area surrounding the slit to redirect an image of the observed field toward a folding mirror and the guiding optical channel. Two identical 50 mm focal-length achromatic
- 145 doublets, mounted back-to-back, re-image the slit plane onto an ASI678MC control camera with a nominal magnification close to unity. Its 3840×2160 pixel sensor, with a $2 \mu\text{m}$ pixel pitch and physical dimensions of 7.68×4.32 mm, therefore provides a theoretical field of view of approximately $8.8^\circ \times 4.9^\circ$ and an angular sampling of about $8.25 \text{ arcsec pixel}^{-1}$. Some vignetting occurs toward the outer edges of this field, but the central region containing the complete 4.6° slit extent remains usable.
- 150 The control camera serves a dual purpose: (1) to determine the spectrograph pointing from the surrounding stellar field and facilitate its coalignment with a wide-field context camera rigidly mounted on the instrument body, and (2) to record the field intersected by the slit during auroral events at substantially higher angular resolution. Once astrometrically calibrated, the



guiding-camera images can also be used to project the position and orientation of the slit directly onto simultaneous all-sky observations.

155 3.3 Detector

The detector is a Sony IMX585-AAMJ1 CMOS sensor, with a pixel size of $2.9 \mu\text{m}$ and 3856 pixels along the spectral axis. This sensor was selected for its excellent near-infrared sensitivity and, importantly, for its smooth and monotonic spectral quantum-efficiency curve, free of interference fringes. The quantum efficiency reaches a peak of 90 % (around 450 nm) and remains high in the near-infrared, with an estimated value of 48 % at 850 nm. The intrinsic read noise is only 1.2 electrons,
 160 typical of the best modern CMOS sensors. This configuration is implemented in the Player One Uranus-M Pro Mono camera, which is used as the science camera of NORVIS (Sect. 4.2). Because the IMX585 is a CMOS detector, spatial binning along the slit is performed after read-out; this read-out architecture is explicitly taken into account in the noise budget.

However, given the small pixel size of this sensor, the reciprocal spectral dispersion of NORVIS is $\rho \simeq 0.188 \text{ nm.pixel}^{-1}$, which allows spectral images to be significantly oversampled relative to the spectral resolution element (see following section).
 165 This feature makes it possible to apply a post-processing step above the optical cutoff frequency (hence non-destructive), consisting of an optimal filter that very effectively removes the impulsive (non-Gaussian) noise typical of CMOS sensors. This procedure brings the effective noise per pixel down to only 0.8 electrons. Considered together with the quantum efficiency, this result indicates that the instrument approaches photon-noise-limited performance under suitable signal conditions.

The sensor is cooled by a Peltier module in the commercial camera used with NORVIS. The measured dark-signal rate of
 170 the IMX585 sensor is 0.0005 electron per second at the characteristic operating temperature of -20°C , making thermal noise entirely negligible.

3.4 Wavelength coverage and spectral resolution

A central design feature of NORVIS is its ability to access two complementary spectral domains with the same optical core, switching between them by a single small rotation of the diffraction grating, of the order of 1° , and without any refocusing
 175 being required. This property is operationally important during observations, where rapid and reproducible reconfiguration is essential.

In the visible configuration, the instrument covers 380-860 nm in a single acquisition. The optics provide a remarkably constant image quality over this entire domain, such that the spectral resolution is essentially limited by the mechanical slit width of $20 \mu\text{m}$, for an input beam operating at $f/5$. The spectral resolution measured at 550 nm (FWHM) is 1.2 nm, consistent
 180 with the $20 \mu\text{m}$ slit imaged over about 6.5 pixels; the $14 \mu\text{m}$ slit brings it down to about 0.9 nm at the cost of a lower throughput.

This domain encompasses, in a single exposure, the principal auroral diagnostics, including the N_2^+ (0,0) 1NG band at 391.4 nm, the N_2^+ 1NG band at 427.8 nm, the atomic oxygen green line at 557.7 nm, the red doublet at 630.0/636.4 nm, the $\text{H}\alpha$ Balmer line at 656.3 nm, the O I line at 777.4 nm, and the O I line at 844.6 nm.

In the near-infrared configuration, obtained by the small grating rotation described above, the instrument covers approxi-
 185 mately 600-1100 nm in a single exposure. The spectral resolution remains comparable to that of the visible mode ($\sim 1.5 \text{ nm}$).



To separate the diffraction orders, a long-pass filter of type OG580 is inserted ahead of the slit when operating in near-infrared mode.

These optical performance aspects are constant over the entire height of the slit image. This makes it possible, for example, to sum the entire signal collected along the spatial axis of the spectral image, so as to obtain an angularly integrated spectrum with a very high signal-to-noise ratio, without loss of resolution.

3.5 Mechanical implementation

The NORVIS prototype is implemented as a small, lightweight, 3D-printed opto-mechanical structure. This compactness and the reproducible manufacturability of the design are central to the distributed, community-driven observing strategy that motivates the instrument.

The camera interfaces to the spectrograph through a standard T2 coupling, making the instrument compatible with the majority of astronomical cameras on the market.

Tests have demonstrated that this mechanical design retains the initial adjustments very well, including under low-temperature conditions (typically -20°C).

3.6 Daytime solar calibration

A practical and reproducible calibration of both the dispersion law and the instrument response is obtained in daylight by observing sunlight diffused by a spectrally neutral white screen. Spectralon-type reflectors² are ideal for this task.

The Fraunhofer lines of the solar spectrum are used as references to establish the instrument's wavelength-to-pixel relation. This calibration is automated by means of a cross-correlation algorithm between the observed spectrum and the reference solar spectrum.

The instrument response, that is, the way the instrument reacts to the incoming light flux as a function of wavelength, is derived by comparing the signal recorded when observing the screen facing the Sun with the extraterrestrial spectral solar flux distribution, corrected for atmospheric transmission at the time of measurement. This procedure is likewise automated, the reduction software incorporating a simplified atmospheric-transmission model including Rayleigh scattering, Mie scattering, and ozone absorption. The procedures above yield a robust *relative* spectral response, which is sufficient for the emission ratios that constitute the primary auroral diagnostics. The relative response is displayed in Figure 4.

Establishing an *absolute* radiometric scale in R/nm will be addressed in a dedicated calibration campaign. The planned strategy relies on laboratory measurements using a 12-inch integrating sphere (Labsphere US-120-SF) illuminated by a 1000 W quartz-halogen lamp through a double monochromator (Bentham DTMc300). This setup is expected to provide a calibrated reference illumination at selected wavelengths, enabling the absolute response of NORVIS to be determined and the second-order contamination in the red and near-infrared spectral range to be quantified.

²<https://www.labsphere.com/product/spectralon-diffuse-reflectance-material/>

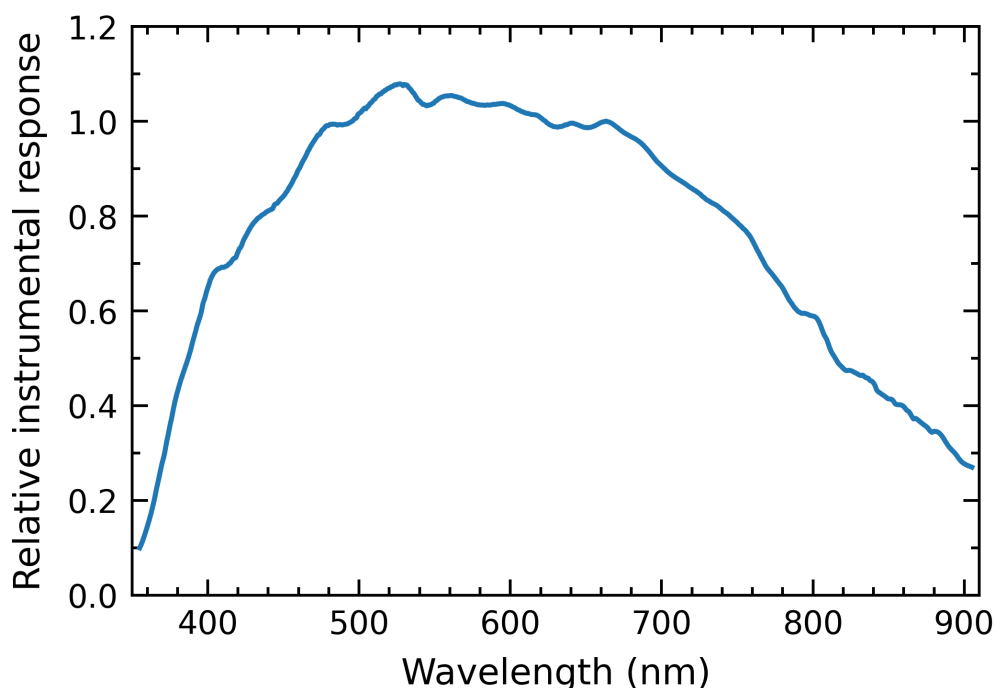


Figure 4. Relative spectral response of NORVIS derived from solar illumination of a Spectralon screen and normalized at H α (656.3 nm).

4 Acquisition, processing, and data-management framework

NORVIS is conceived as a complete observing system rather than as an optical spectrograph alone. Field operation, real-time visualization, instrument control, data archiving, and automated spectral reduction are integrated within a dedicated, fully open-source software environment. This is a deliberate design choice, consistent with the distributed, researcher - citizen-science observing strategy that motivates the instrument: a copy of NORVIS can be deployed and operated by any observer using freely available code, and its data enter the common archive in a form directly comparable with that of every other unit. The overall organization is summarized in Fig. 5: an on-site segment, embedded with each instrument, performs acquisition, real-time quality control, and local archiving, while a shared cloud segment provides long-term storage, automated reduction, and access to the calibrated products. The main implementation choices are documented in Appendix A.

4.1 System architecture and instrument control

The on-site segment follows a client-server architecture. All instrument functions, camera control, observation sessions, observatory metadata, storage and calibration management, system monitoring, and optional telescope-mount control, are implemented in a single service running on a low-power computer embedded with the instrument, and are exposed through a documented network interface complemented by real-time channels for images and telemetry. Detector control is delegated

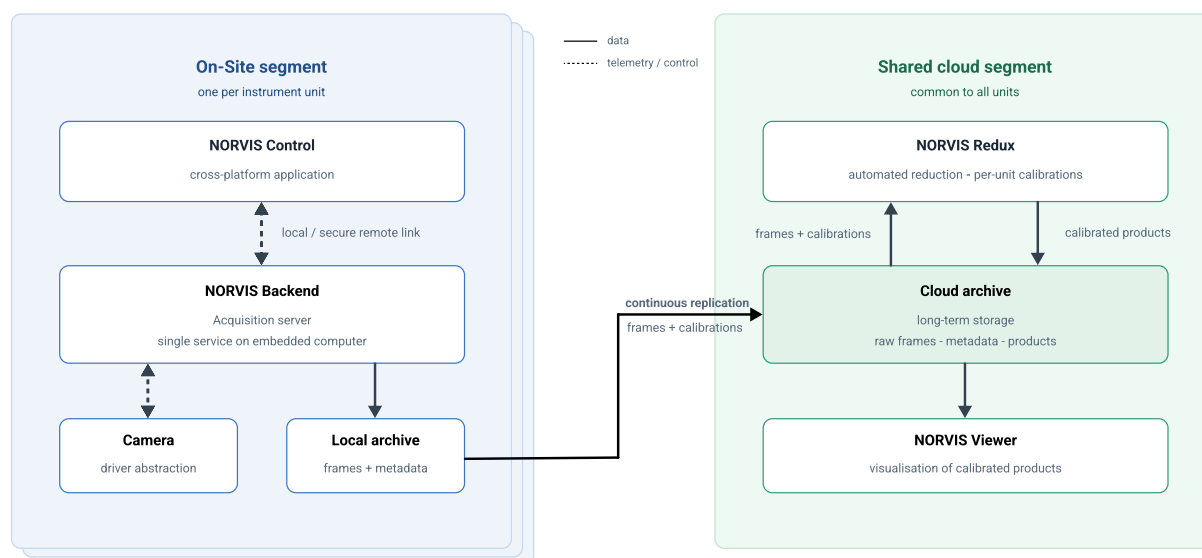


Figure 5. End-to-end architecture of the NORVIS observing system. Each instrument unit embeds an acquisition server operated from a cross-platform application over a direct, local, or secure remote connection. Acquired frames and their metadata are continuously replicated to a shared cloud archive; an automated reduction service processes each science frame using the calibration data of its instrument unit and publishes the calibrated products to the archive that feeds the NORVIS Viewer application

230 to a driver-based hardware-abstraction layer, so that the system is not tied to specific camera models. Because the complete instrument state is accessible through this interface, the control software is fully decoupled from the user interface.

The observer operates the instrument through a single cross-platform application, NORVIS Control (Fig. 6), available on mobile devices and desktop computers from the same code base. The interface is designed for ergonomic field use under auroral observing conditions, including reticle and region-of-interest overlays and one-handed operation on a mobile device in
 235 the dark.

4.2 Three-camera acquisition

As already introduced in Sect 3.2 and Sect. 3.3, NORVIS integrates three cameras, each addressable independently. The *science* camera, a Player One Uranus-M Pro Mono based on the Sony IMX585 sensor, records the dispersed spectrum. The *slit-context* camera, a ZWO ASI678MC, images the field at the slit plane and is used to identify and center the targeted region of the
 240 auroral structure on the slit. The *wide-field* context camera, based on a Sony IMX477 sensor, provides a wide-field view of the auroral display and of the pointing context. Figure 7 presents the NORVIS instrument with these elements. The cameras can be configured and operated individually or simultaneously, supporting coordinated multi-camera acquisition.

Live images from the three cameras are streamed from the instrument to the NORVIS Control application, providing the observer with simultaneous access to the spectral acquisition and its pointing context. Through NORVIS Control, each camera
 245 can be configured independently, with control of exposure time, gain, offset, and, where available, sensor cooling. Acquisition

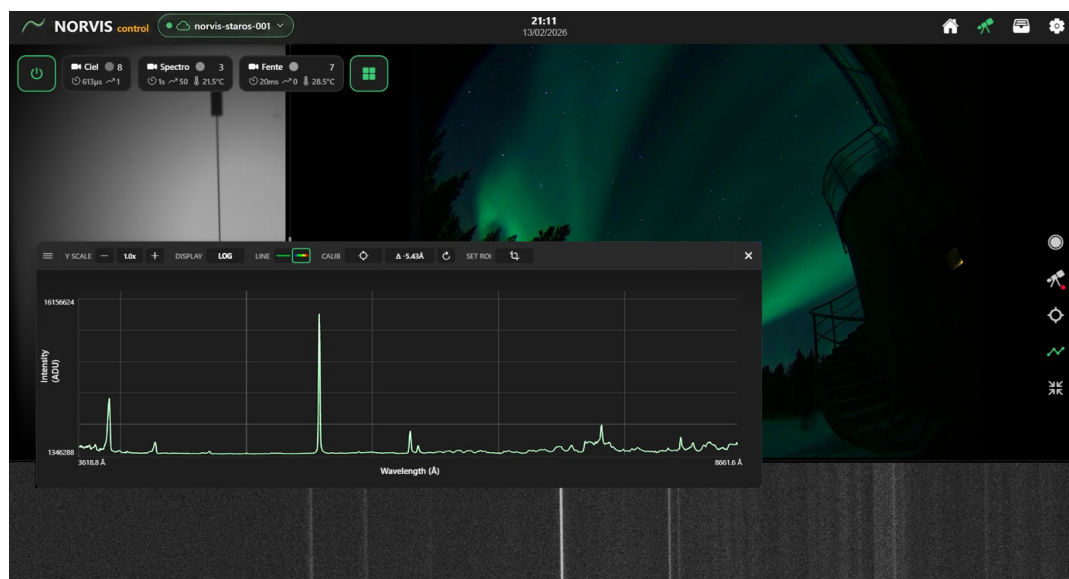


Figure 6. Screenshot of the NORVIS Control application during the February 2026 campaign at Skibotn. The interface shows the status of the three cameras (top left), the live wide-field view (right), the slit-context panel (left), the raw science frame (bottom), and a preview of the spectral profile obtained by binning a user-selected region of the science frame along the spatial axis. The slit-context camera was not yet implemented at the time of the campaign; the corresponding panel displays a static placeholder image.

status and sensor telemetry are continuously reported to the application. The science channel preserves the full 16-bit radiometric depth required for spectral analysis, and per-frame histograms are computed directly from the raw data, before any compression, to assist exposure adjustment under low-light conditions.

250 An immediate one-dimensional preview of the acquired auroral spectrum is also displayed in NORVIS Control. For each science frame, an observer-defined region of interest is summed along the spatial direction to produce an intensity profile. This profile can optionally be converted to wavelength using the dispersion relation established from the daytime solar calibration (Sect. 3.6) and is displayed live alongside the camera views. Auroral emission features can therefore be identified and the quality of the acquisition assessed directly in the field, without requiring an off-line reduction step.

4.3 Network modes and remote operation

255 Three network modes cover the intended deployment scenarios. In *hotspot* mode, the embedded computer acts as a standalone WiFi access point to which the application connects directly; this fully autonomous configuration requires no external infrastructure and is the primary mode for portable field campaigns. In *local* mode, the instrument is attached to an existing local network and is controlled from any device on that network. In *remote* mode, the instrument is operated over the Internet through an authenticated, end-to-end-encrypted virtual private network, without any public exposure of the embedded computer. Re-

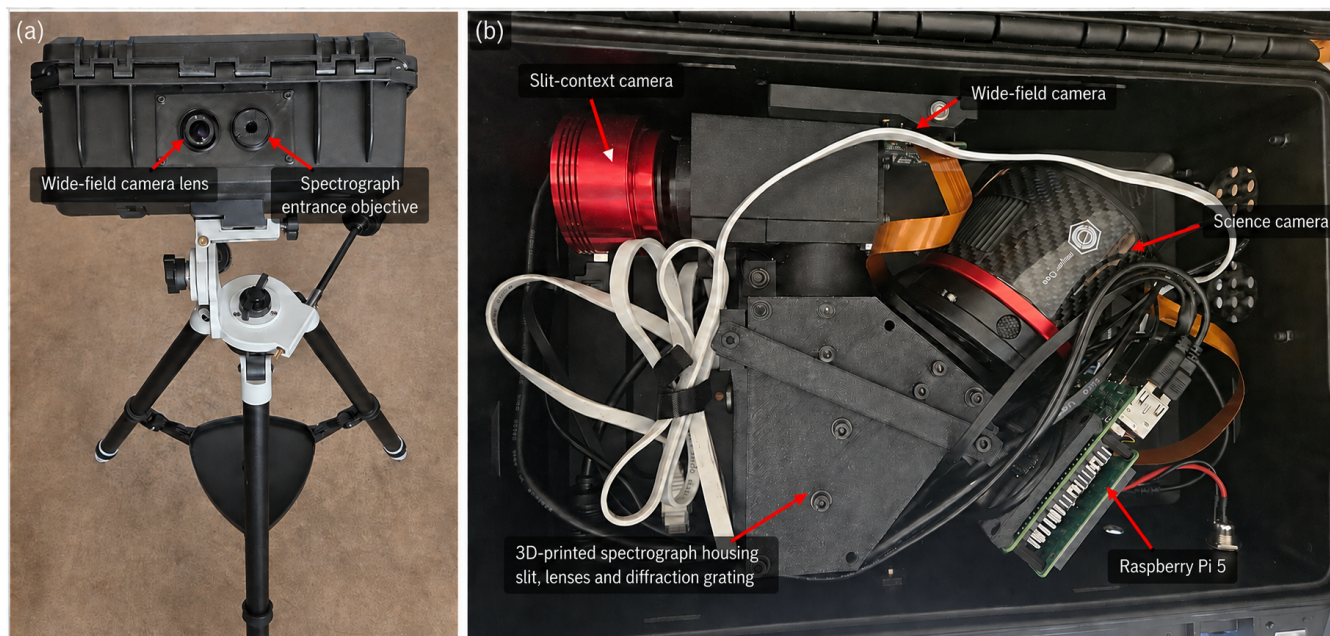


Figure 7. Overview of the NORVIS instrument and its internal assembly. (a) NORVIS mounted on its tripod, showing the wide-field camera lens and the spectrograph entrance objective on the front plate. (b) Internal view showing the slit-context camera, the wide-field camera, the science camera, the Raspberry Pi 5, and the spectrograph components, including the slit, lenses, and diffraction grating, housed within the 3D-printed enclosure.

260 mote operation makes unattended fixed-station deployments and coordinated multi-site campaigns practical while preserving the security of the control interface.

4.4 Data organization, archiving, and metadata

Observations are organized hierarchically by night and by session, each session grouping the frames acquired from the three cameras together with their associated calibration frames (offset, dark, flat, and the solar reference frames from which the dispersion law and the instrumental response are derived; Sect. 3.6). Science and slit-context frames are stored in FITS format with companion quick-look images, and wide-field frames are stored as images carrying the observation metadata. The metadata preserves the key information required for later scientific exploitation, including observing site and observatory coordinates, UTC timestamps, exposure time, gain, detector temperature, instrument configuration, region of interest, and calibration status.

Archiving is designed for unattended operation. A background synchronization process continuously and incrementally replicates newly acquired data to a cloud object store, verifying the integrity of every transferred file and automatically retrying failed transfers; a configurable retention policy subsequently reclaims space on the embedded computer once files have been safely replicated. Complete sessions can also be copied in the field onto external mass storage. Within the application, a library view allows past sessions and individual spectra to be inspected, compared, and, where relevant, assembled into time-lapse



products from the wide-field camera. These tools are designed to be usable by non-specialist observers, which is essential for
275 the broad researcher-citizen scientist observing network targeted by the project.

4.5 Automated spectral reduction

Spectral reduction is fully decoupled from acquisition and runs as a dedicated cloud service, NORVIS Redux, fed by the
archive described above. Science frames replicated to the object store are registered as reduction jobs, either individually or
in small batches, a configurable trade-off between the latency of the products and the overall processing efficiency. Each job
280 associates the science data with the reference calibration data (offset, dark, flat, and instrumental response) of the corresponding
instrument unit, which are built and updated from the calibration frames archived with the observing sessions. Jobs are queued
and executed by a pool of workers, so that the processing capacity scales with the size of the observing network rather than
with the embedded computers. Job status and progress are reported in real-time, and the resulting products, the calibrated one-
dimensional spectrum, quick-look previews, and tabular exports, are written to a dedicated product archive, which constitutes
285 the single data source for the viewer application used to browse, visualize and analyse the observations of the network.

The reduction chain itself is strictly separated from this orchestration layer: each processing step is a published, literature-
based algorithm, and the sequence applied to auroral frames is declared in a versioned, per-instrument configuration (Ap-
pendix A). The chain performs the detector-level corrections, offset and exposure-scaled dark subtraction, together with the
filtering of the impulsive CMOS noise discussed in Sect. 3.3, followed by the geometric rectification of the spectral image
290 and the extraction of the extended auroral emission. Because the instrument carries no calibration lamp, the dispersion law
established by the daytime solar calibration (Sect. 3.6) is refined for each exposure using nightglow emission lines recorded
on either side of the auroral signal, thereby correcting instrumental flexure and thermal drift, and the extracted spectrum is
divided by the instrumental response. Every reduction finally records digital fingerprints of its input frames, of the pipeline
configuration, and of the resulting spectrum, so that identical inputs verifiably yield identical products, a prerequisite for the
295 consistent combination of spectra acquired from different observers and sites.

The NORVIS Viewer, shown in Fig. 8, has also been developed to easily display the reduced spectra from NORVIS Redux,
and to perform some preliminary spectra selections.

5 First auroral observations and operational validation

The first NORVIS auroral campaign was conducted at the Skibotn Observatory, Norway, in February 2026 under winter field
300 conditions. Over several observing nights, approximately 1200 spectra were acquired and reduced, providing a first operational
test of the complete observing chain, including field deployment, pointing, acquisition, reduction, and visual inspection of
the data. At the time of the February 2026 campaign, the instrument did not yet include the slit-context camera described in
Sect. 4.2, which was implemented after the campaign. The instrument proved easy to operate in practice. Owing to its compact
optical design and lightweight mounting configuration, the line of sight could be rapidly adjusted during the observations,
305 allowing the spectrograph to be pointed toward different parts of evolving auroral structures.

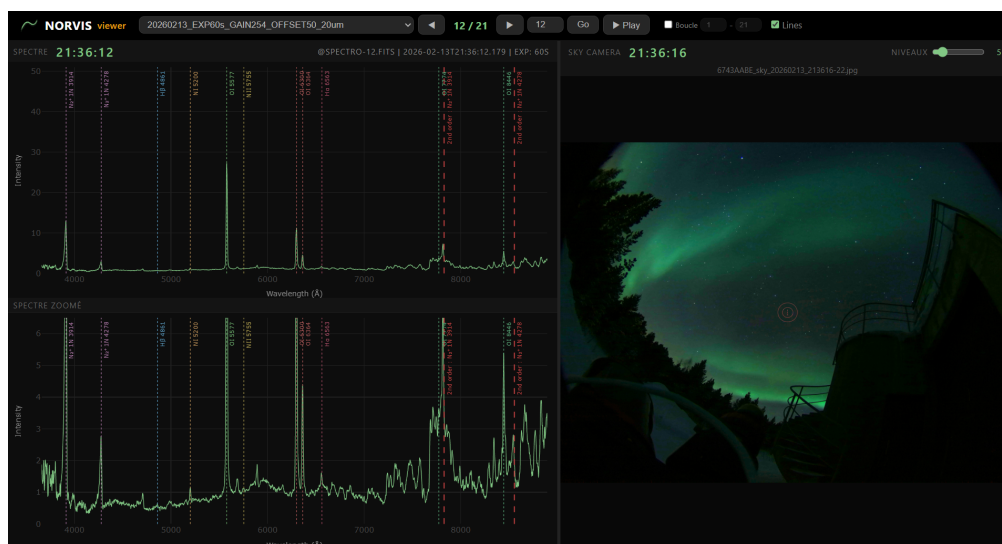


Figure 8. Screenshot of the NORVIS viewer, the web application used to browse the reduced spectra produced by the automated reduction pipeline. The view shows the full reduced spectrum (top left), a zoomed version revealing the weaker features (bottom left), and the simultaneous wide-field image (right) with the spectrograph pointing indicated by the circle marker. The example is a 60 s exposure obtained on 13 February 2026 at 21:36:12 UTC, with the line-identification overlay activated.

This operational flexibility is important for auroral spectroscopy. Unlike fixed field-aligned instruments, NORVIS can be repointed during an event in order to follow discrete arcs, sample different apparent altitudes within an auroral form, or perform simple angular scans such as almucantar observations. The February 2026 campaign therefore served not only as a test of the optical performance of the instrument, but also as a validation of its ergonomics for real-time auroral observations.

310 In the following subsections, we show a few representative examples illustrating the spectral content obtained during the campaign. These examples are not intended as a full scientific analysis of the events, but as a demonstration of the instrumental capabilities of NORVIS under realistic observing conditions.

5.1 Representative spectra

Figure 9 presents a typical NORVIS observation obtained on 16 February 2026. The wide-field context image (Figure 9a) shows
 315 that the spectrograph line of sight intersects the lower part of a bright auroral arc. For this exposure, the pointing direction was approximately $Az = 81^\circ$ and $Alt = 53^\circ$, placing the slit on the lower portion of the visible auroral structure, and the exposure time is 30 s. This configuration provides a useful example of a discrete auroral arc observed under favorable signal conditions.

The corresponding integrated spectrum (Figure 9b) illustrates the broad spectral coverage of NORVIS and the simultaneous detection of several key auroral emissions. In the blue part of the spectrum, the N_2^+ first negative bands at 391.4 and 427.8 nm
 320 are clearly detected. The visible spectrum is dominated by the strong [O I] 557.7 nm green line. The red region contains the [O I] 630.0/636.4 nm doublet, which remains very weak in this example, consistent with the instrument pointing toward

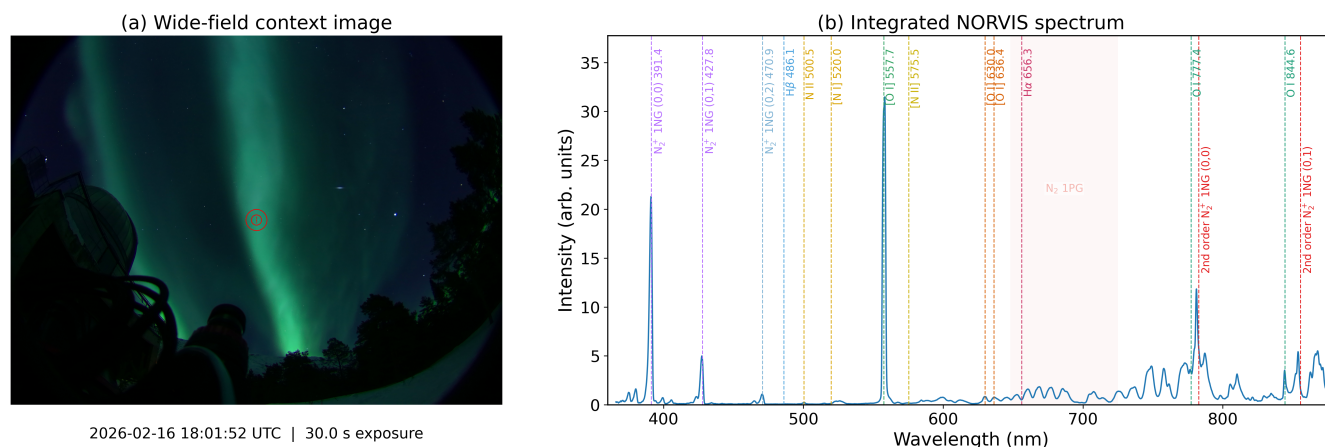


Figure 9. Representative NORVIS observation of the lower part of an auroral arc, obtained on 16 February 2026 at 18:01:52 UTC with a 30 s exposure. (a) wide-field context image showing the spectrograph line of sight intersecting the lower region of the visible auroral structure, with the red center indicator referring to the slit position. (b) Integrated NORVIS spectrum associated with the same exposure. The main identified emissions include the N_2^+ first negative bands at 391.4 and 427.8 nm, the N_2^+ feature at 470.9 nm, $[O \text{ I}]$ 557.7 nm, a faint $[O \text{ I}]$ red doublet at 630.0/636.4 nm, and $O \text{ I}$ 777.4 and $O \text{ I}$ 844.6 nm. Broad shaded regions indicate spectral intervals where N_2 1PG contributions are expected to be significant.

the lower part of the auroral arc. Strong molecular band emission is also observed in the red spectral range, in particular between approximately 650 and 680 nm, where N_2 1PG contributions become prominent. The observation was obtained during strongly disturbed geomagnetic conditions, with a K index of 8 at Tromsø magnetic observatory in the time bin containing the exposure, supporting the interpretation of this spectrum as representative of active, substorm-time auroral precipitation. Tromsø magnetometer data indicate a substorm expansion of about 600 nT during the observation, followed immediately afterwards by a larger decrease reaching about 1200 nT.

The extended wavelength coverage also provides access to the $O \text{ I}$ 777.4 nm line and to the spectral region around 844.6 nm. The latter must, however, be interpreted with caution because of possible second-order contamination from shorter-wavelength N_2^+ emissions. This example demonstrates that NORVIS can record, in a single exposure, prompt molecular emissions, atomic oxygen lines, and red/near-infrared molecular structures within the same auroral context image.

A second representative case obtained on 14 February 2026 is shown in Fig. 10. In contrast to the previous example, the wide-field context image indicates that the NORVIS line of sight intersects the upper part of a faint auroral arc (Figure 10a). The pointing direction for this exposure was approximately $Az = 96^\circ$ and $Alt = 38^\circ$, again with an exposure time of 30 s. The observation was obtained during the substorm growth phase, with a K index of 3 in the corresponding time bin, increasing to 6 in the following time bin. Tromsø magnetometer data indicate a substorm expansion of about 800 nT immediately afterwards.

The associated integrated spectrum (Figure 10b) again shows the main auroral emissions across the full NORVIS spectral range. Compared with the lower-arc case, the $[O \text{ I}]$ 630.0/636.4 nm red doublet is relatively more prominent. This is consistent

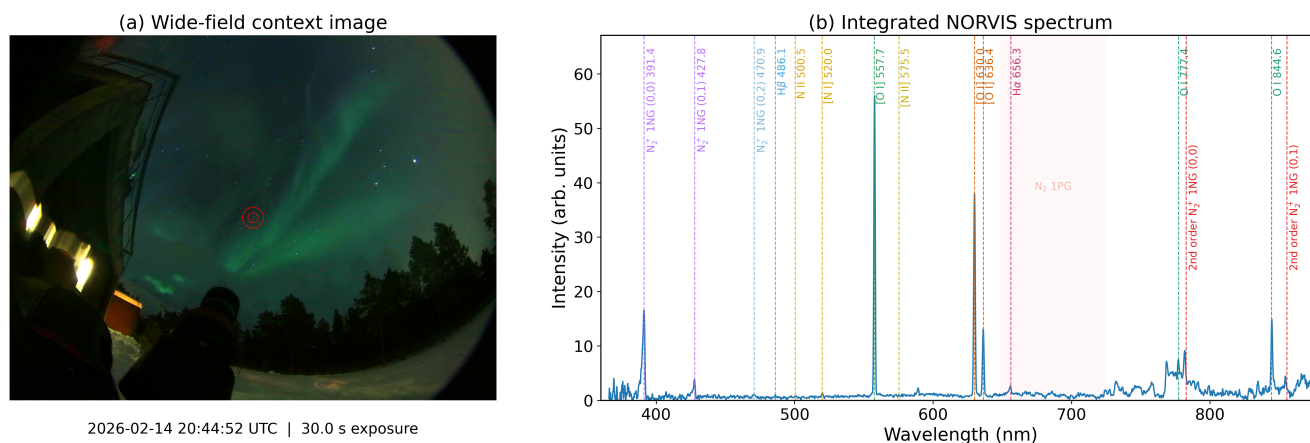


Figure 10. Representative NORVIS observation of the upper part of an auroral arc, obtained on 14 February 2026 at 20:44:52 UTC with a 30 s exposure. (a) Wide-field context image showing the spectrograph line of sight intersecting the upper region of the visible auroral structure. (b) Integrated NORVIS spectrum associated with the same exposure. The main auroral emissions and band systems are indicated. Compared with the lower-arc case, the [O I] 630.0/636.4 nm red doublet is more prominent, consistent with a larger contribution from higher-altitude oxygen emission along the line of sight.

with the viewing geometry: by sampling the upper part of the visible auroral structure, the line of sight is expected to include
 340 a larger contribution from higher-altitude oxygen emission regions, where the long-lived [O I] 630.0 nm transition is favored
 while the [O I] 557.7 nm line remains strong. A spectral feature is also visible in the H α region around 656.3 nm, together with
 molecular emissions and red/near-infrared structures.

Both examples illustrate the ability of NORVIS to capture changes in the spectral balance associated with different pointings
 within auroral structures. The interpretation remains line-of-sight integrated and should not be considered as a direct altitude
 345 retrieval. Nevertheless, the contrast between this case and the lower-arc observation demonstrates that the combination of wide-
 field context imaging and broadband spectroscopy provides a practical way to relate spectral variability to auroral morphology.

NORVIS is able to provide a physically rich auroral spectrum from a single acquisition, combining prompt molecular
 emissions, long-lived atomic oxygen lines, and access to the hydrogen Balmer spectral regions within the same dataset. In
 the present subsection, only the spectrum integrated over the full slit is considered, with the aim of illustrating the general
 350 instrumental capability and the spectral content obtained in real observing conditions. Spatially resolved extractions along the
 slit are possible when the signal-to-noise ratio is sufficient, especially during intense auroral events, but they are not exploited
 quantitatively in the present manuscript.

5.2 Almucantar observations of the H α spectral region

An almucantar sequence was performed in order to test the capability of NORVIS to sample the H α spectral region at a
 355 fixed elevation of about 45° while varying the azimuthal direction. This observing geometry provides a simple way to probe

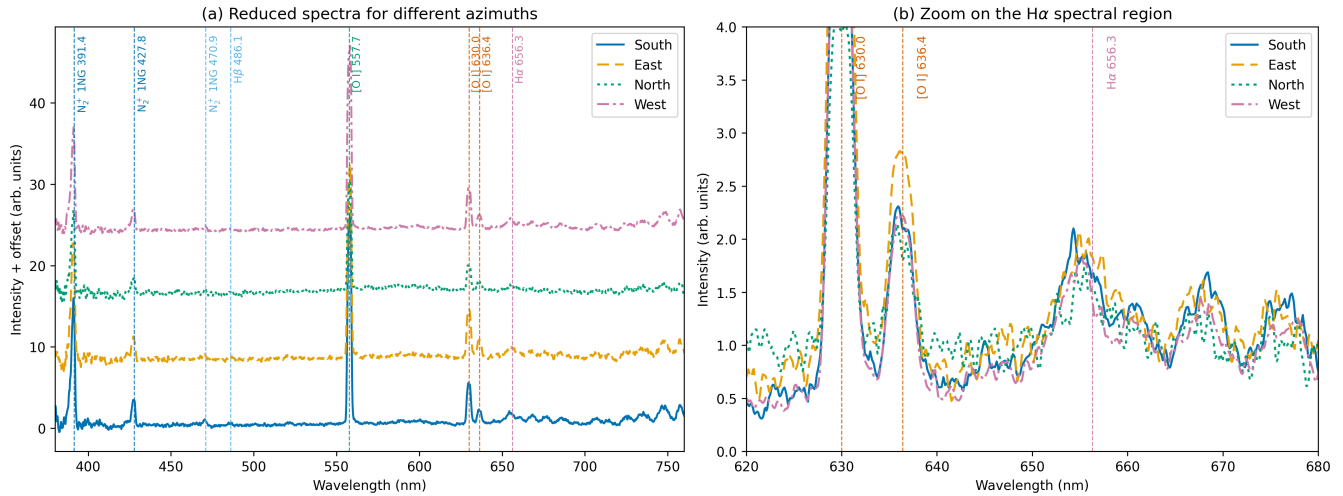


Figure 11. Reduced NORVIS spectra obtained during an almucantar sequence at fixed elevation (45°) for four azimuthal directions: South, East, North, and West. (a) Full spectra between 380 and 760 nm, vertically shifted for clarity. The positions of the main auroral emissions and band heads are indicated, including N₂⁺ 1NG at 391.4 and 427.8 nm, H β 486.1 nm, [O I] 557.7 nm, the [O I] red doublet at 630.0/636.4 nm, H α 656.3 nm. (b) Zoom on the 620–680 nm interval, showing the [O I] 630.0 and 636.4 nm lines together with the H α spectral region. A feature close to 656.3 nm is visible in all four azimuthal directions, suggesting a widespread contribution in the H α region at this elevation (45°).

the angular distribution of red auroral emissions under comparable line-of-sight elevation conditions. Four reduced spectra obtained toward the South, East, North, and West directions are shown in Fig. 11.

The full spectra show the expected auroral emissions, including the N₂⁺ 1NG bands near 391.4 and 427.8 nm, the [O I] 557.7 nm green line, the [O I] red doublet at 630.0 and 636.4 nm. In the zoomed spectral interval between 620 and 680 nm, a feature is observed close to the H α wavelength at 656.3 nm for all four azimuthal directions. Since the elevation is kept fixed at about 45° during the sequence, this suggests that a contribution in the H α spectral region is present over a broad range of viewing directions, rather than being confined to a single localized pointing.

However, this spectral region cannot be interpreted by a simple integration around 656.3 nm. The red part of the auroral spectrum contains molecular emissions, including nearby N₂ and N₂⁺ band structures, which can contaminate the H α region. A quantitative extraction of the hydrogen contribution requires a dedicated spectral model including the local continuum, the instrumental response, the [O I] 630.0/636.4 nm lines, molecular band templates, and is currently under development.



6 NORVIS science drivers and diagnostic perspectives

6.1 From broadband spectra to auroral diagnostics

The diagnostic use of NORVIS depends strongly on the observing geometry. For field-aligned observations, classical emission-ratio methods can be applied. Ratios involving emissions such as the N_2^+ ING (0,1) band at 427.8 nm and [O I] 630.0 nm provide constraints on the characteristic energy of the precipitating electrons (Adachi et al., 2017; Cessateur et al., 2026). These diagnostics are more straightforward to interpret for diffuse aurora or quasi-stationary auroral arcs, where temporal evolution, transport, and quenching can be treated in a controlled way. The broad spectral coverage of NORVIS also provides access to ratios involving prompt emissions, such as 391.4/777.4, 427.8/777.4, and 391.4/844.6. These combinations are particularly relevant for discrete aurora because they involve emissions that respond more rapidly to precipitation than the long-lived metastable [O I] emissions at 557.7 and 630.0 nm. Ratios involving O I 777.4 nm and O I 844.6 nm will require the second-order correction discussed in Sect. 3.6.

For observations that are not field-aligned, the diagnostic problem is different. In that case, emission ratios alone cannot be interpreted as direct energy proxies without accounting for the observing geometry. However, the combination of wide-field context imaging and slit spectroscopy provides access to the apparent morphology of the auroral structure. By pointing at different regions of an arc, NORVIS can sample different parts of the emitting volume, as illustrated by the lower- and upper-arc examples presented in Sect. 5.1. In this configuration, synthetic spectra are not used only as column-integrated references. Instead, altitude-resolved synthetic spectra computed for different precipitating electron energies can be compared with the observations to identify the combinations of emission altitude and precipitation energy that best reproduce the measured spectrum (Barthelemy et al., 2025). For example, the relative contributions of the prompt N_2^+ bands, [O I] 557.7 nm, and [O I] 630.0 nm vary strongly with altitude. Comparing the observed spectra with synthetic spectra calculated at selected altitudes using the TRANSOLO model (Lummerzhim and Lilensten, 1994) therefore provides a geometry-aware interpretation framework, as displayed in Fig. 12. The figure is used here as an illustration: for field-aligned observations, such simulations support emission-ratio diagnostics based on column-integrated spectra. For non-field-aligned observations, they motivate geometry-aware comparisons between observed spectra, wide-field context images, and synthetic spectra integrated along representative lines of sight.

6.2 Continuum and aurora-like emissions beyond classical aurora

A second motivation for NORVIS is the growing number of auroral and aurora-like emissions that cannot be understood from colour or narrowband images alone. STEVE is the best-known case: it appears as a narrow mauve-white subauroral structure, distinct from classical aurora and stable auroral red (SAR) arcs, and is associated with strong subauroral ion drifts (SAID) and ionospheric heating rather than conventional particle precipitation (MacDonald et al., 2018; Gallardo-Lacourt et al., 2018; Archer et al., 2019; Gillies et al., 2019). Spectroscopy showed that STEVE is dominated by broadband emission rather than by a standard auroral line spectrum (Gillies et al., 2023).

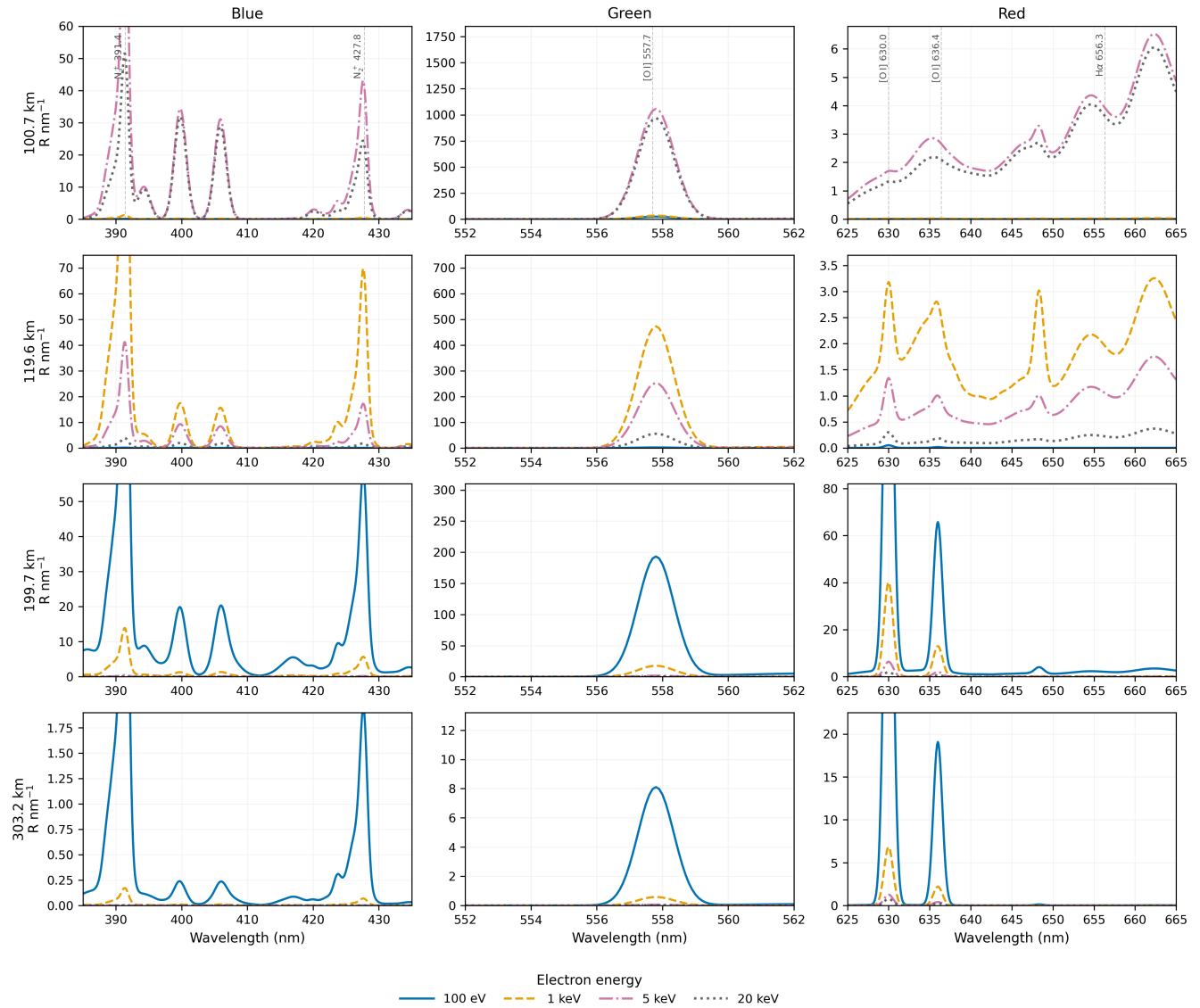


Figure 12. Synthetic auroral spectra at selected altitudes for monoenergetic electron precipitation at 100 eV, 1 keV, 5 keV, and 20 keV obtained from the TRANSOLO model (Barthelemy et al., 2025). The spectra were convolved with a Gaussian instrumental profile with a FWHM of 1.2 nm to reproduce the spectral resolution of NORVIS. The columns show representative spectral intervals in the blue, green, and red parts of the NORVIS spectral range, while the rows correspond to different sampled altitudes. The curves illustrate how the relative contributions of N_2^+ bands, [O I] 557.7 nm, [O I] 630.0 nm, and red molecular emissions depend on both precipitating electron energy and altitude.



Similar non-traditional auroral emissions have been reported near the poleward boundary of the auroral oval. Dayside continuum emissions over Svalbard show broadband enhancements across the visible range, possibly extending into the near-infrared, while still following auroral dynamics and precipitation (Partamies et al., 2025). Dayside broadband emission may involve structured molecular pseudo-continuum from highly excited N_2 and N_2^+ rather than a simple NO/NO₂ continuum (Dayton-Oxland et al., 2025). Similar ambiguities appear inside or near the auroral oval (Nanjo et al., 2024). FAEs and picket-fence structures further blur the boundary between precipitation-driven aurora and locally generated ionospheric emissions (Dreyer et al., 2021; Whiter et al., 2021; Nanjo et al., 2026b). Dune aurora represents another unusual emission occurring at comparatively low auroral altitudes, often toward the equatorward part of the auroral region and potentially associated with dusk-sector processes. The broadband coverage of NORVIS, including the Balmer H α and H β regions, could help assess whether proton precipitation contributes to these events (Grandin et al., 2026).

These cases show why broadband spectroscopy is needed. A pale or white structure in an RGB image may be a true continuum, a molecular pseudo-continuum, a blend of unresolved bands, or simply overlapping discrete emissions along the line of sight. NORVIS is designed to address exactly this ambiguity: it records the classical auroral lines, molecular bands, Balmer emissions, and possible continuum background in a single acquisition, while preserving the wide-field context.

6.3 Toward a distributed researcher—citizen scientist NORVIS network

NORVIS was developed within a researcher—citizen scientist collaboration, and this is part of the instrument concept rather than an accessory. The goal is not only to build a compact spectrograph, but to make broadband auroral spectroscopy deployable by trained citizen scientists. In practice, the observing sequence is deliberately simple: the observer points the instrument toward the target auroral structure, starts the acquisition from a smartphone or desktop interface, after which the data are automatically uploaded to the centralized archive and processed by the dedicated reduction pipeline.

This operational simplicity is essential for rare and transient phenomena. STEVE, continuum-like emissions, FAEs, picket fences, and unusual continuum events are often first detected by wide-field colour cameras or by citizen scientists. They are also spatially narrow, short-lived, or geographically localized, making it difficult to capture them with fixed high-performance instruments. A distributed NORVIS network would add a standardized spectroscopic layer to these observations, progressively building a large and homogeneous data set while substantially increasing the likelihood of capturing both common auroral regimes and rare, atypical, or as-yet unidentified phenomena.

For classical auroral arcs, multi-site NORVIS observations would allow spectra to be recorded from different viewing geometries through the same structure. Combined with wide-field context images and synthetic spectra, this opens a path toward geometry-aware interpretation and, ultimately, tomographic constraints on auroral emissions. For unusual aurora-like events, the same network would provide the spectral confirmation needed to distinguish classical line emissions from molecular pseudo-continuum or continuum-like structures.

The first coordinated deployment of NORVIS instruments is planned within the framework of the SCOSTEP program in November 2026. During the initial observing campaign, two instruments will operate at fixed sites at IRF in Kiruna, Sweden, and at the Skibotn Observatory in Norway. A third unit will be deployed at different locations in Svalbard, potentially including



Ny-Ålesund and the Kjell Henriksen Observatory (KHO) near Longyearbyen, while a fourth mobile unit will operate in the Kilpisjärvi region of Finland. Following the campaign, these four instruments will form the initial permanent network, with
435 installations at IRF in Kiruna, Sweden (67.84°N, 20.41°E), the Skibotn Observatory in Norway (69.35°N, 20.36°E), KHO in Svalbard, Norway (78.15°N, 16.04°E), and the Nyrölä Observatory in Finland (62.34°N, 25.51°E).

This strategy is naturally aligned with citizen-science initiatives (Kataoka et al., 2024; Grandin et al., 2025). NORVIS does not replace large facility instruments such as ASIS, MISS, HiTIES, EISCAT, or TReX. Its role is different: to provide portable, reproducible, centrally archived broadband spectra at locations where no permanent spectrograph is available.

440 7 Conclusions

NORVIS translates the Star'Ex heritage into a dedicated auroral instrument: compact, portable, reproducible, and optimized for diffuse emissions rather than stellar point sources. The first campaign at Skibotn Observatory in February 2026 validated the concept under real auroral conditions. The observations confirm that a single NORVIS exposure can cover the main visible and red/near-infrared auroral diagnostics, from the N_2^+ 1NG bands at 391.4 and 427.8 nm to [O I] 557.7 nm, [O I] 630.0/636.4 nm,
445 the $H\alpha$ region, O I 777.4 nm, O I 844.6 nm, and the red N_2 1PG bands.

NORVIS requires no dedicated infrastructure and can be deployed rapidly in field conditions at a wide range of suitable observing sites. Its low power consumption also allows operation from a portable power bank, providing considerable freedom in the choice of location and observing geometry. NORVIS can be repointed during an event to sample different parts of an auroral structure or to perform angular scans. This makes it possible to combine classical field-aligned emission-ratio
450 diagnostics with observations obtained from other viewing geometries and interpreted using wide-field context images and synthetic spectra.

NORVIS is designed to be operated by both researchers and trained citizen scientists. Its observing workflow allows an auroral structure to be identified, targeted, and observed spectroscopically with minimal setup, using either a smartphone or desktop interface. The acquired data are transferred to the central archive and processed by the NORVIS reduction pipeline.
455 The relative spectral calibration allows emission ratios to be compared between observations, while centralized processing provides a consistent reduction procedure for data acquired at different sites.

A remaining instrumental issue is the characterization of second-order contamination in the red and near-infrared part of the spectrum, particularly around the O I 777.4 nm and O I 844.6 nm spectral lines. An absolute calibration in rayleighs would further strengthen quantitative comparisons with emission models, but is not required for diagnostic applications based
460 on relative emission ratios. The upcoming coordinated campaign, with deployments in Kiruna, Skibotn, Svalbard, and the Kilpisjärvi region, will provide the first test of NORVIS as a distributed spectroscopic network. The subsequent permanent installations, including KHO in Svalbard and Nyrölä in Finland, will extend this capability toward long-term observations of classical aurora as well as atypical emissions such as STEVE, fragmented aurora-like emissions, picket fences, dune aurora, and continuum-like events.



465 **Appendix A: Implementation of the acquisition and reduction software**

This appendix records the main implementation choices behind the framework described in Sect. 4. These details are provided for reproducibility and to facilitate reuse of the software.

A1 Acquisition backend and client application

The acquisition backend is a Python service built on the FastAPI framework and served by a Uvicorn ASGI server on the Rasp-
470 berry Pi 5 embedded computer. It exposes a versioned REST API, organized into resource groups for the cameras, observation sessions, observatory metadata, storage and calibration, system monitoring, logs, timelapse products, cloud synchronization, and the telescope mount, together with WebSocket endpoints dedicated to real-time data and telemetry. The science and slit-context cameras are controlled through the INDI framework (`indiserver` and its Python binding `PyIndi`), which provides a uniform, driver-based hardware abstraction; logical camera roles are bound to physical INDI devices through an explicit,
475 persisted mapping, so that camera models can be substituted without modifying the software. The wide-field camera is operated directly through the `rpicam-still` interface. The client application is implemented in React Native with the Expo toolchain, and its desktop builds are produced with the Tauri framework, which wraps the shared front end in a lightweight native shell using the system web renderer. Science frames are streamed as 16-bit grayscale PNG images over a dedicated binary WebSocket, with optional server-side downsampling for mobile clients; the context cameras are streamed as compressed
480 frames over separate channels, and per-frame histograms are computed server-side on the raw data before any compression.

A2 Remote operation

In remote mode, connectivity is provided by Tailscale, a WireGuard-based mesh virtual private network that establishes an authenticated, end-to-end-encrypted overlay network between the observer's device and the embedded computer. The backend listens simultaneously on plain HTTP, for hotspot and local access, and on HTTPS for remote access, the TLS certificate
485 being issued for the machine's stable name within the private network. No inbound port forwarding or public exposure of the embedded computer is required, and traversal of network address translation is handled transparently by the VPN layer.

A3 Archiving and synchronization

The cloud-synchronization worker uploads newly acquired files to an S3-compatible object store (Cloudflare R2 in the current deployment; AWS S3 is equally supported). It tracks the state of every file in a local SQLite database, verifies each transfer by
490 content hashing, and retries failed transfers with exponential backoff; the local-retention policy deletes on-instrument copies only after successful, verified replication. Copies of complete sessions to external USB or SSD mass storage report their progress to the client over a WebSocket.



A4 Reduction service and pipeline configuration

The reduction service, NORVIS Redux, consists of a REST API and a pool of asynchronous workers coordinated through a message broker; jobs, instrument definitions, and their calibration state are persisted in a document database, while raw uploads, calibration masters, and reduced products are held in three separate buckets of the object store, and all transfers between clients and storage use presigned, per-user URLs. Every reduction executes a versioned pipeline description (a YAML preset) that names each algorithm and its parameters for a given instrument unit. For auroral frames, the sequence comprises: offset subtraction; dark subtraction scaled by exposure time; adaptive median filtering based on the local median absolute deviation, which suppresses the impulsive (telegraph-type) noise of the CMOS sensor while preserving narrow line profiles; mild Gaussian smoothing; affine rectification of the tilt and slant of the spectral image, with an optional polynomial smile correction; construction of a nightglow reference spectrum from the detector bands on either side of the auroral signal; wide-aperture extraction of the auroral trace; per-exposure refinement of the zero point of the dispersion law against a reference nightglow line; division by the instrumental response; and continuum normalization. All algorithms are implemented in an openly published spectroscopy library (<https://pypi.org/project/spectro-kernel>), each rooted in the published literature, and the same engine can equally be executed as a command-line tool or as a Python library, guaranteeing that a spectrum reduced locally and one reduced by the cloud service are strictly identical. Each job records content hashes of its input frames, of the pipeline configuration, and of the resulting spectrum, making every reduction verifiable and reproducible.

Code availability. All software components of the NORVIS observing system are open source, covering the complete chain described in Sect. 4: the embedded acquisition server and its cross-platform observer application, the NORVIS Redux automated reduction service, and the viewer application. The source code is available at <https://github.com/staros-projects/norvis-backend>, <https://github.com/staros-projects/norvis-app>, <https://github.com/staros-projects/norvis-redux>, and <https://github.com/staros-projects/norvis-viewer>.

Author contributions. GC led the study and manuscript writing. GC, CB, GB, MLL, VD, and OG performed the Star'Ex and NORVIS observations. CB, GB, MLL, VD, OG, and GC designed and built the NORVIS instrument. GB and MLL developed the NORVIS software suite, including NORVIS Control, NORVIS Redux, and NORVIS Viewer. GC performed the data analysis presented in Sect. 5. HL, MB, MGJ, DB, UB, AC, FD, RDO, JDK, MG, KK, RM, SN, and NP contributed to the scientific development of the NORVIS project and to the preparation and coordination of future NORVIS observations and deployments. All authors contributed to the scientific discussion and interpretation of the results and reviewed the manuscript.

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