

Thank you very much for your valuable comments and suggestions for improvement. We will answer your questions below, and we will revise the manuscript reflecting your comments.

Abstract

L1 and Abstract: *The current abstract does not include any direct results or new findings of this paper itself. It describes the novelty of the experiment, but not the novelty of the findings.*

This study presents a new method to investigate ionospheric electric field structures. Using tomography, we successfully derived the three components of the ion velocity at each location. This allows us to show from observations that key assumptions in previous studies—such as negligible collisions at the observation altitude and purely horizontal electric fields—are reasonable. Compared to previous approaches, our method estimates the electric field with fewer assumptions.

L4 “The effective approach”: *Could the authors clarify in what sense this approach is considered effective?*

This approach is effective because it allows us to directly visualize and observe ion motion controlled by the electric field. In-situ rocket and radar observations allow direct measurements of ions, but they are limited to single-point observations. Optical observations enable us to derive three-dimensional velocity fields and obtain their corresponding spatial maps.

L7 “A novelty of the experiment is...”: *At L94, the authors state that the difference between ALIS and ALIS_4D is the use of an EMCCD instead of a CCD. Combining these two sentences, does this mean that the only novelty of the experiment, compared to previous studies, is the use of an EMCCD?*

Experiments of this type have not been conducted with ALIS. The previous wording may have been misleading, but improvements to ALIS and ALIS_4D are not the main novelty of this study. The novelty of this study is that we reconstruct Ba^+ ion movement in three dimensions using tomography. This provides a detailed study of ion dynamics with a resolution of 500 m and 0.1 s.

L11 “quite a long time”: *How long is this period?*

We can observe the clouds by cameras for almost 30 minutes.

Introduction

L15 “current systems”: *Could they also explain more why the current system is important for understanding this coupled ionosphere – magnetosphere system?*

L15” Various observational approaches”: *The introduction discusses rocket, satellite, and ground-based measurement approaches. These techniques have different horizontal and vertical observation ranges, but the current text does not describe these differences and their implications.*

L20 “were small, less than 10 mV/m”: *It may be useful to mention how small these values are compared to the background.*

L21 “altitude dependent ... were reported”: *This sentence appears inconsistent with the statement at L22 that “no significant altitude variation was observed.”*

L24 “On the other hand, charge oscillations were observed”: *The meaning of this sentence and relation to the previous sentence are unclear. Please rephrase it.*

L26 “spacecraft”: *This literature appears in the middle of a paragraph introducing rocket studies. How is it related to that context? Spacecraft studies are introduced starting at L37.*

L37” attempted”: *The authors could add more information to this sentence explaining why satellite measurements were attempted.*

L42 “strong”: *How strong are these?*

L44 “relatively large”: *Relative to what, and how large? Please specify.*

L45 “... However...”: *The reviewer does not understand the implication of this “however” or the logical connection between the preceding and following sentences. Please clarify the intended contrast.*

L50 “Strong”: *Please explain how strong, and relative to what.*

L51 “3 s,”: *Is this about optical or EISCAT observation ?*

L53 “the two”: *Please clarify what “the two” refers to.*

L53 “response”: *Does this imply any interaction between the radar and the electric*

field?

L57 “downward field-aligned currents”: Could the authors describe how these currents are related to the electric field?

L58 “background electric field was...canceled by a polarization electric field”: Please explain the mechanism responsible for this.

L 59 “this study”: Please consider rephrasing “this” to avoid possible ambiguity.

L62 “but have relatively limited resolution. However,...”: The reviewer does not understand how these sentences about Clayton et. al., are connected by “but” and “however.” Please rephrase.

L66 “As a result, it was difficult to separate temporal variations from spatial variations based on the observations alone.”: The reviewer does not understand this as a conclusion from the preceding sentence.

L67 “temporal and spatial scales smaller than... not be detected”: This limitation applies to any observation technique. What are intended to mean here?

L68 “barium clouds”: Active ionospheric experiments using chemical releases, including barium, have been conducted for many years. The authors cite Fahleson et al. in the beginning, but additional previous studies and results relevant to the present work could be introduced if there are any.

We thank you for your helpful comments. We will address these points and incorporate the revisions into the revised manuscript. We will substantially revise the Introduction in the revised manuscript in response to your comments.

Experiment

L75 “23 March 2023”: The storm events in March 2023 including March 23 have been studied by several authors already. Can authors find any relationship between their study to previous studies? e.g,

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023JA032145>

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023SW003728>

As seen in these papers, the EISCAT radars were operating on March 23, and one of their objectives should have been to support the BROR experiment. Were there any EISCAT results that could be relevant to the current work? Also, with regard to previous EISCAT–rocket studies, such as the cited works by Lanchester et al. or Aikio et al.? In particular, ion-drift measurements or electric field/FAC estimates derived from the radar data would be highly relevant.

EISCAT was operated in a special mode during the BROR experiment. However, because the signal-to-noise ratio was relatively low, it is difficult to make meaningful comparisons of the small-scale dynamics associated with the aurora. It may be possible to present averaged values in the revised manuscript.

L84 “moved under influence of the electric field”: *Similar to the comment above, strong thermospheric winds were reported on 23-24 March 2024 storm (see Oyama et al 2024 above). Did the authors estimate the possible influence of thermospheric winds?*

Our study accounts for the influence of the neutral wind on the motion of barium ions. The thermospheric wind velocities were determined from the motion of neutral strontium clouds observed by optical instruments. We will compare the neutral wind velocities obtained in our experiment with the papers you mentioned in the revision.

L96 Figure 2: *What does the yellow point on the map represent? No description is provided.*

The yellow dot on the map indicates the ALIS_4D Nikkaluokta station, but it was not used during the BROR experiment, so we plan to remove it.

2.2 Instruments and Data

L104 “strontium”: *Why was only the camera at Esrangle used to measure strontium? In addition, were any results from these strontium measurements considered in the analysis from Esrangle in Figure 3?*

Only the ALIS_4D camera at Esrangle was operated with the 460.7 nm filter to observe neutral strontium, whereas the other cameras were configured with the 493.4 nm filter

to observe ionized barium clouds. This configuration was chosen because the main goal of the BROR experiment was to study the small-scale electrodynamics in the auroral ionosphere through the motion of ion clouds. The initial version of the manuscript did not include a description of the analysis of the Esrange strontium data. In the revised manuscript, we will include approach to estimate the thermospheric neutral wind and to evaluate the possible influence of ion-neutral collisions on the barium ion motion. We will also revise the relevant figures.

L112 “too weak to be detected”: *Is this conclusion based on experimentally established results from previous studies, or is it derived from the observations in the present study? In Figure 4, both cameras show isolated round structures near the arc (for the Kiruna camera, one appears near the center of the image). What are these features?*

The data of the Watec cameras at Kiruna and Tjautjas are the images taken with a band-pass filter for the auroral 557.7 nm emission. The isolated round structures in these images are likely associated with strontium lines at 550.4, 552.1, 553.4 and 554.0 nm. For lower-altitude clouds, barium oxidation competes with ionisation. BaO is characterised by a rich electronic-vibrational spectrum in the visible range and may contribute to cloud images recorded by Watec cameras. Ba⁺ emission lies outside the wavelength range of the camera filter.

3 Data processing and analysis

L118 “Figure 5”: *Please indicate where the fourth cloud is located in all of the Ba-related sub-figures in Figure 5, and specify how many clouds are present in total.*

We will revise the figure to make the cloud locations clearer, as illustrated in the Figure R1.

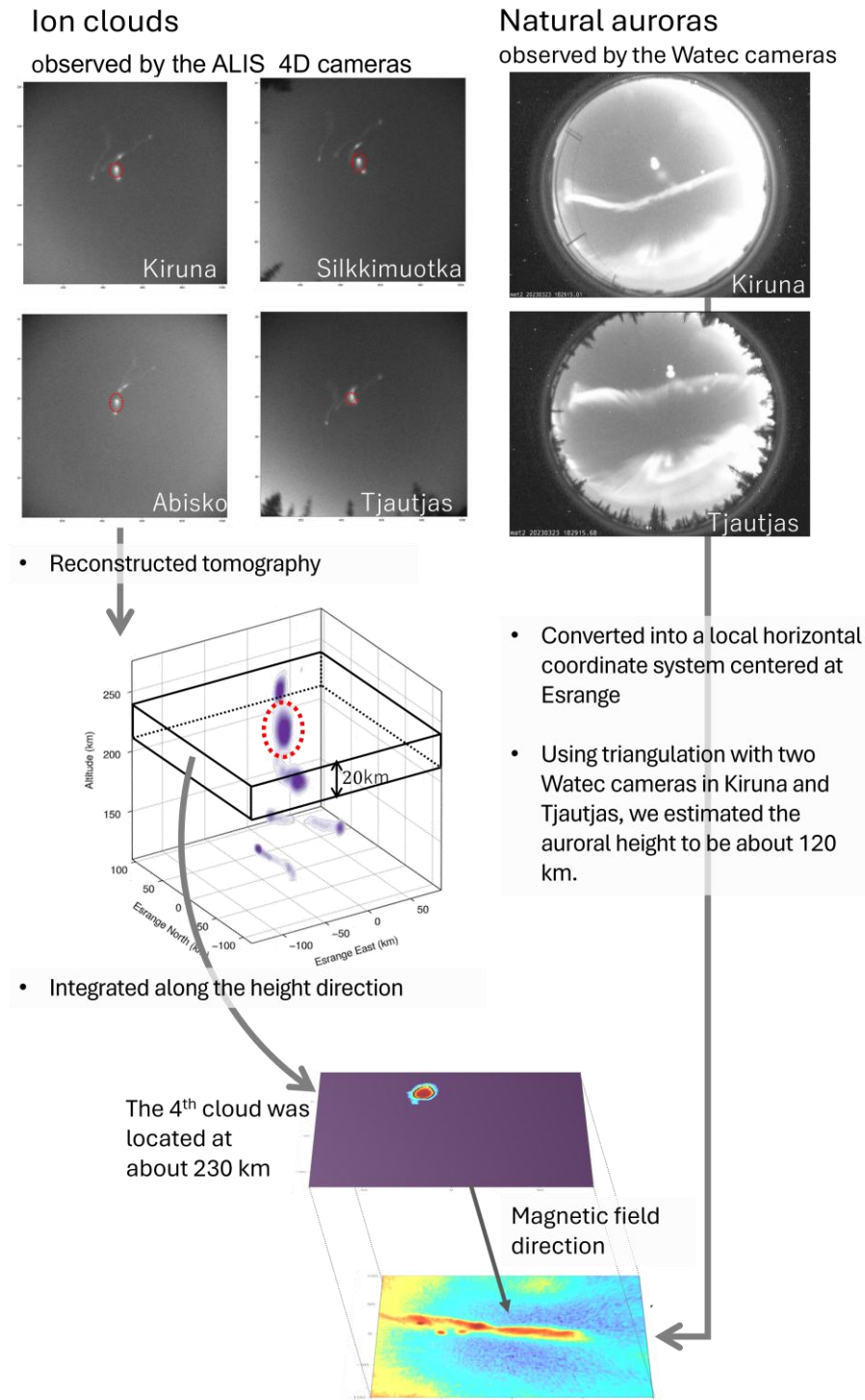


Figure R1 Figure 5 with the position of the fourth ion clouds clearly indicated

L123 Figure 6: This reconstruction figure seems that some of the early ion clouds reached lower altitudes, close to the auroral altitude around 120 km. If this interpretation is correct, these clouds may be more suitable for analyzing the electric field in the vicinity of the aurora.

The fourth cloud was the only cloud that deformed during the auroral passage, and

therefore it was selected for detailed analysis. We were fortunate during the BROR experiment in that an auroral arc traversed a barium ion cloud released at altitudes above 200 km. At these altitudes, the gyrofrequency of Ba⁺ ions exceeds the collision frequency. The ion motion is controlled predominantly by the ExB drift. It is possible to infer the fine-scale structure of the electric field and current systems associated with the auroral arc. We will clarify this point in the revised manuscript.

L125 “a vertical range of ± 10 km around the altitude at which the cloud intensity reaches its maximum.”: Please explain in more detail how the altitude of maximum Ba intensity is determined. Is this done by comparing mapped images using altitude as a parameter from all four stations?

The maximum intensity of barium emission is derived from tomography. Therefore, the vertical position is determined with a spatial resolution of 500 m.

For example, the altitude profile at 18:26:30 is shown in the Figure R2. By horizontally (x–y plane) integrating the reconstructed three-dimensional intensity distribution, we estimate that the fourth cloud is located at an altitude of approximately 222 ± 10 km. Within this range, we identify the point (X, Y, Z) with the maximum intensity. We will clarify this in the revised manuscript.

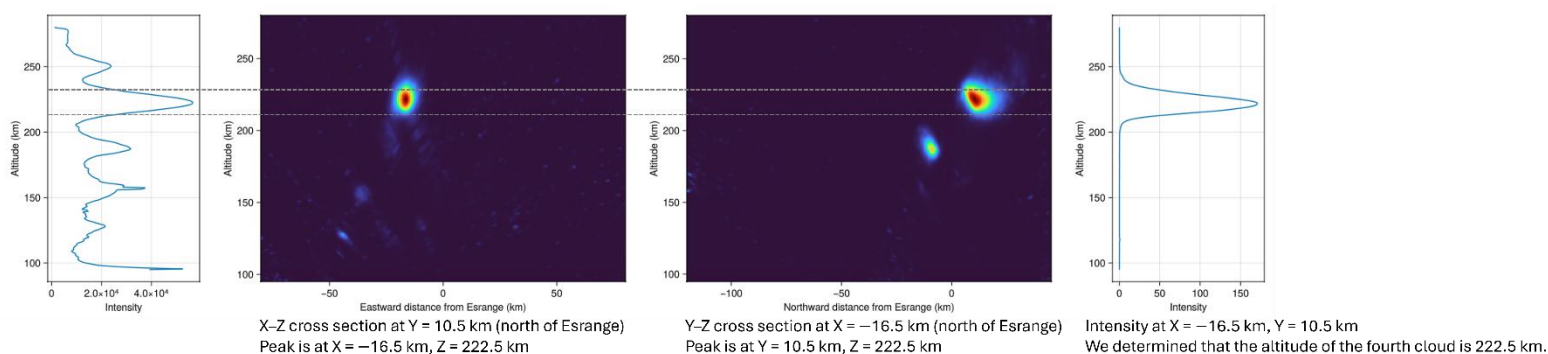


Figure R2 Schematic diagram for determining the altitude of the fourth cloud

L 133 “we shifted the cloud data to the height at an altitude of 120 km”:

The objective of this projection needs more explanation.

This reconstruction procedure appears to assume that electric field variations can be ignored over the 100-km altitude range between approximately 120 and 230 km. How do the authors justify this assumption in the case of an auroral arc?

Moreover, this projection gives the impression that the analysis does not fully utilize the capabilities of the experimental design. If the reviewer interpreted it correctly, as the tomographic results in Figure 6 show, the total set of ion clouds spans a much larger altitude and horizontal range than the fourth cloud alone, with some clouds extending down toward auroral altitudes. In principle, this experiment could provide not only horizontal motion but also information on vertical deformation/motion.

Also, similar to a comment before, the EISCAT Tromsø radar was operational on that day and should provide plasma parameters, and likely most relevant for this study, altitude variation of plasma parameters including ion-drift.

It is generally accepted that magnetic field lines in the ionosphere are approximately equipotential down to about 90 km altitude, where electrons become non-magnetised. Although there is evidence for field-aligned electric fields at ionospheric altitudes, these are often considered small compared to the variations in the horizontal electric field components.

Above about 200 km altitude, ions, including heavy barium ions, are mainly driven by the $E \times B$ drift and can be used to directly infer electric field variations. At lower altitudes, ion-neutral collisions and neutral winds increasingly affect ion motion, making it difficult to reliably infer the electric field from ion dynamics.

The aim of this study is to investigate the fine structure of electric fields and currents within individual auroral arcs using a specific dataset from the BROR experiment. Additional barium cloud release data are used to examine several phenomena related to the electrodynamics of the auroral ionosphere, such as field-aligned electric fields and the physicochemical behavior of barium in the thermosphere.

Regarding EISCAT Tromsø, the signal-to-noise ratio is not sufficient for a reliable quantitative comparison of ion-drift with the BROR results.

L138 “...green points. A blue line...”: *The blue lines in Figure 7 do not appear to represent the observed auroral arc accurately, as they differ noticeably from the grayscale structure. Fitting a straight line to an auroral arc does not seem physically justified or effective, especially at 18:30 UT. At 18:25, no auroral arc is visible in the image, but only the blue lines are shown.*

The image at 18:25 is cropped to focus on the fourth cloud, but an auroral arc can be

seen extending in a curved shape. The blue straight line is drawn based on that configuration.

As you pointed out, fitting a possibly curved auroral arc with a straight line may introduce differences in the spatial relationship with the aurora. For comparison, we also show the auroral structure and resulting electric field when fitting the arc using a fifth-order polynomial. However, the overall results do not change significantly.

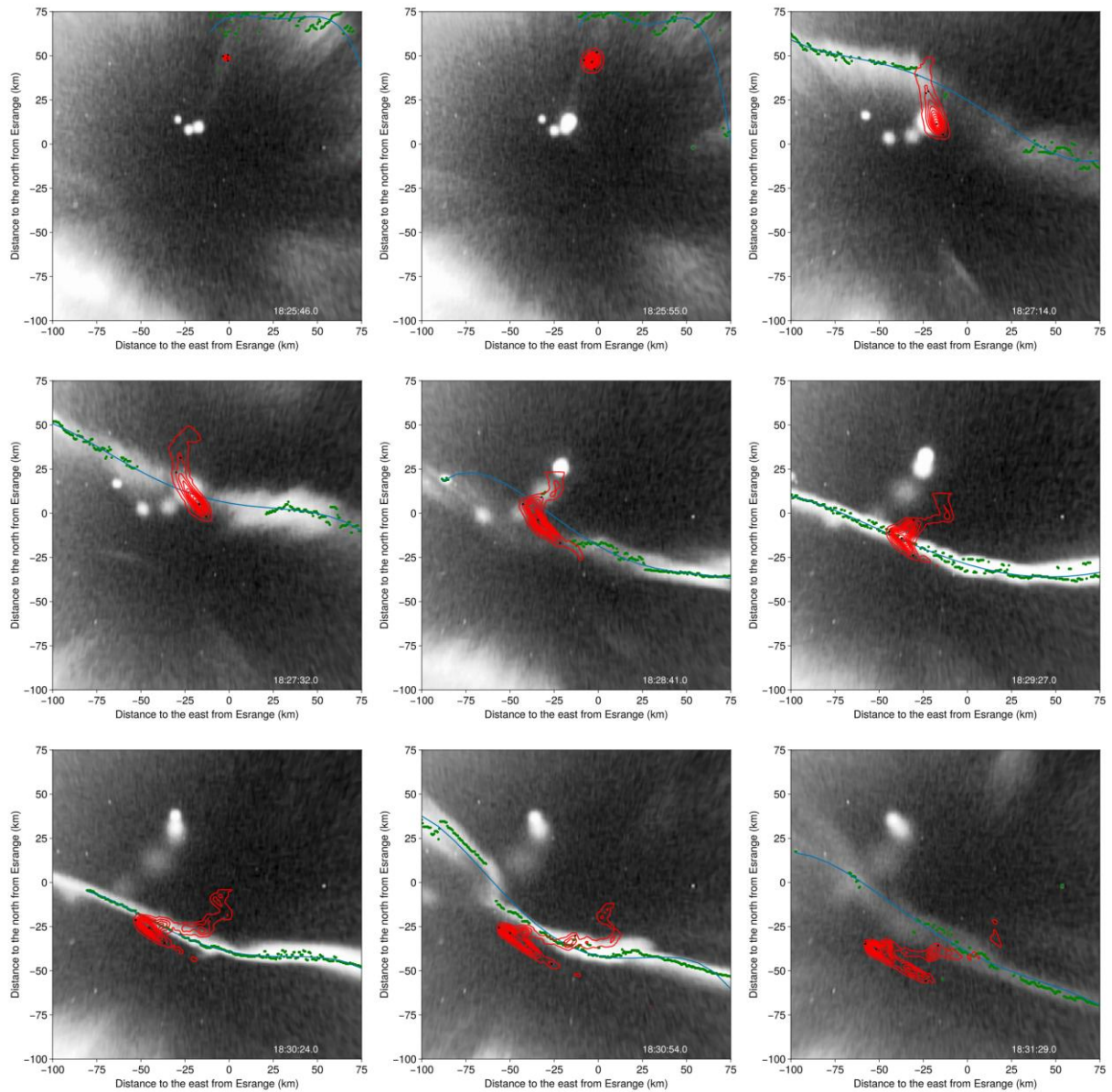


Figure R3 Superpositions of the fourth cloud and the auroral arc at 18:25:46 UT, 25:56, 27:14, 27:32, 28:41, 29:27, 30:24, 30:54, and 31:29, when fitting the arc using a fifth-order polynomial.

L139 “The fourth cloud projected”: The reviewer assumes that the red tracings in Figure 7 represent the projected cloud structures from Figure 6. However, at 18:25

these appear only as very small red points in Figure 7. Based on Figures 6 and 7 alone, it is difficult for the reader to verify whether the red circles in Figure 7 correctly correspond to the fourth cloud shown in Figure 6.

To improve clarity, the authors should consider adding the auroral arc outline also in Figure 6 for comparison, and/or provide the geolocation (latitude, longitude, and altitude) of the fourth cloud. This would allow readers to follow the temporal and spatial development of the fourth cloud more easily.

In addition, as noted earlier, the bright round structures in the auroral images create confusion if they are not related to the barium clouds. Are these bright features indeed unrelated to the BROR cloud releases? A clear explanation is needed to avoid misinterpretation.

We would like to clarify that we analyze only the fourth cloud among the multiple clouds. This cloud was released at around 18:25 UT and is the cloud that is tracked in Figure 7. To make the correspondence between Figures 6 and 7 easier to follow, we will revise the figure caption and text to state explicitly that the red contours in Figure 7 are obtained from the tomographic reconstruction of the fourth cloud and then projected to the 120-km altitude plane along the magnetic field line. We will also provide additional images for all times shown in Figure 7 as shown below.

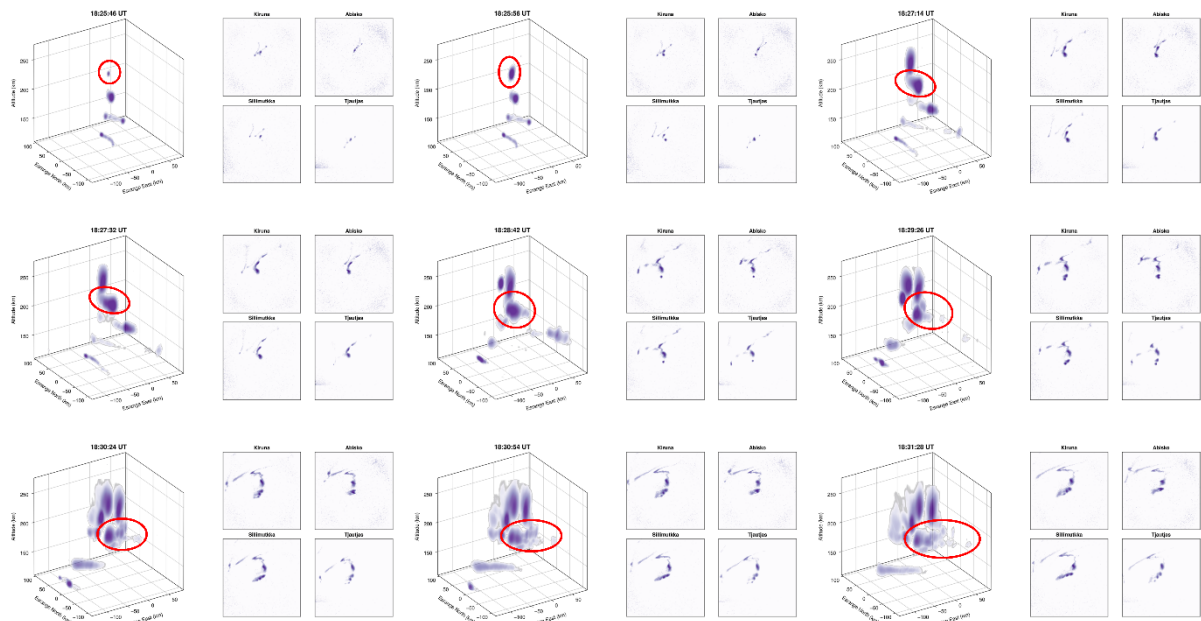


Figure R4: Tomographic images for all times shown in Figure 7. Red circle indicates the fourth cloud in each image.

The bright circular structures seen in the Watec images of the aurora are likely associated with emissions from strontium. They are therefore related to the BROR releases, but they do not represent the Ba⁺ emission traced in this study. The ion cloud emission is not clearly captured by the Watec cameras equipped with the green-line filters.

L147 “We selected four points to characterize the cloud deformation”. *The reviewer assumes that this paragraph is intended to describe Figure 8, although Figure 8 is never mentioned in the main text.*

We will revise the text as follows: We selected four points to characterize the cloud deformation, as illustrated in Figure 8.

L162: “7-s moving average”: *High-resolution imaging was a key novelty of this experiment. Please explain whether this novelty is preserved when the data are averaged.*

The 7-s moving average was applied only to the derived velocity time series, not to the original high-cadence image data or tomographic reconstruction. The 0.1-s observations were used to track the cloud position and to confirm that no significant sub-second or few-second perturbations were present. Thus, the high temporal resolution is still essential for validating the temporal behavior of the cloud motion, even though the final velocity curves are smoothed for display and interpretation. Because the cloud displacement between adjacent time steps is small relative to the spatial grid size, the unsmoothed velocity appears discrete; the moving average was used to show the slowly varying drift more clearly. We will clarify that this smoothing reduces sensitivity to variations shorter than several seconds, but the electric-field structures discussed here occur on longer time scales and are not significantly affected.

L164: “60s, 100 s”: *Please specify the times in UT so that readers can compare them directly with the optical figures.*

We will update the manuscript to include UT in the manuscript together with the elapsed time, e.g., 60 s (18:26:46) and 100 s (27:26).

L172 “Watec images also include BROR clouds”: *This sentence seems to contradict the statement in line 112, creating confusion for the readers. Please explain this point more clearly.*

As stated in response to line 139, neutral components are included in the observations. The Watec images were obtained using a 558 nm filter and therefore include emissions from strontium clouds. However, these clouds are not the Ba ion clouds analyzed in this study. We will clarify this distinction in the revised manuscript.

L178 “distance of each point from”: *Related to earlier comments, is the projection from 230 km down to 120 km include any geometric effects? For example, can the spatial distance between two points become larger or smaller after the projection? Any such distortion could directly affect the distance/velocity calculation.*

At present, the transformation is treated as a simple parallel shift. The barium clouds analyzed in this study are distributed within an area of approximately 200 km × 200 km above Esrange, over which the inclination of the magnetic field lines changes by only about 0.5°. This could introduce a distortion of roughly 1 km. Since this corresponds to only about two grids in the tomographic reconstruction, we consider that the distortion is not large enough to significantly affect the results. We will include this estimate and clarify the possible geometric effect of the projection in the revised manuscript.

L188 “vertical velocity along the z-axis”: *Please clarify whether this computation is performed before or after the tomographic reconstruction shown in Figure 6. If it is derived after tomography, then the vertical resolution is limited to approximately 20 km, the it could impact the interpretation of Figure 11.*

A more essential question concerns the vertical motion of the barium clouds: how much of the observed descent can be explained by natural gravitational settling, and how much is attributable to electric-field-driven motion?

Aslo, in Sergienko et al., 2024, a vertical motion of ions was reported as an unexpected finding. Is there any connection to the current study?

The vertical velocity shown in Figure 11 is derived after the tomographic reconstruction. In the reconstruction, the cloud intensity is obtained on a 500-m grid, and the altitude of the maximum intensity is traced as a function of time for the selected representative points. We will clarify this procedure in the revised manuscript and also describe the uncertainty of the altitude determination.

In the original manuscript, the effect of gravity was not taken into account. However,

including this effect resulted in better agreement with the observations. In the revised manuscript, we will present these improved results.

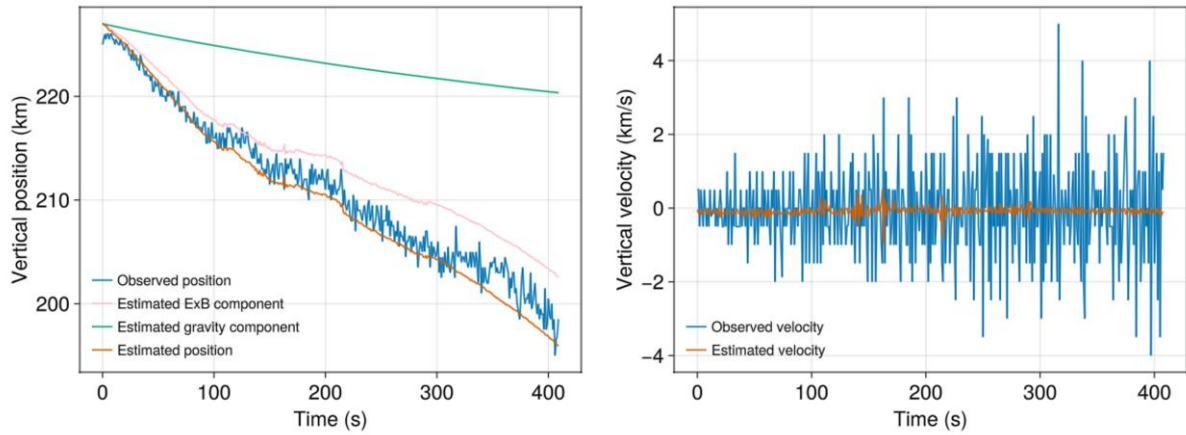


Figure R5. (Left panel) Altitude as a function of time since the fourth cloud release. The blue line shows the observed altitude. The pink line represents the altitude decrease expected from the $E \times B$ drift component, while the green line represents the decrease expected from gravity. The orange line shows the sum of these contributions and thus the estimated altitude. The blue and orange lines are generally in good agreement.

(Right panel) Vertical velocity as a function of time since the fourth cloud release, using the same velocity data as in the current manuscript. The blue line shows the observed velocity, while the orange line shows the estimated velocity. Because of the large scatter in the velocity data, we consider the altitude comparison shown in the left panel to be more suitable for inclusion in the revised manuscript.

The unexpected vertical velocities mentioned in Sergienko et al. (2024) was associated with clouds formed by barium release at altitudes lower than 190 km and was interpreted as possibly indicating a field-aligned electric field. The fourth cloud analyzed in the present paper is located at a higher altitude, around 230 km, and its vertical motion can be explained without invoking such an additional field-aligned electric field. We will clarify the relation to Sergienko et al. (2024) and distinguish the present result from the lower-altitude case discussed there.

4 Results and discussion

L193: This section 4 is titled “Results,” but in practice the material presented in Section 3 also contains results. The distinction between the two sections is therefore

unclear.

In the revised manuscript, we will change the title of this section to a more appropriate one, such as "Discussion" or "Estimation of electric fields".

L199 “for the altitude of approximately 230 km treated in this study,”: *One of the most significant methodological questions in this study concerns how the lower-F-region electric field is being characterized when the mapped auroral structures are located at E-region heights. The manuscript does not clearly explain the physical justification for interpreting an electric field at 230 km based on features mapped to ~120 km. The E-region is highly collisional compared to lower F-region, so the electrodynamic behavior, and therefore the inferred electric field may be sustainably different.*

The magnetic field lines at the ionospheric altitudes are almost equipotential. So the mesoscale (>tens of meters) electric fields at altitudes of 230 km and 120 km are the almost same. The auroral images taken by the Watec cameras are used only for obtaining the geographical position of the auroral arc and its connection to the field-aligned current system.

What is really different at these altitudes is the electrical currents, but they are not the subject of this paper. The vertical motion of the three lowest barium ion clouds created during the BROR experiment indicates the potential presence of the field-aligned electric field at a distance from the auroral arc. This electric field is very interesting as an auroral electrodynamic phenomenon, but it is too small for a noticeable influence on the total electric field structure in the ionosphere.

L 213 “a function of distance from the auroral arc”:

One of the central viewpoints of this manuscript is the characterization of the electric field as a function of distance from the auroral arc, then compared with modeled fields derived from IMAGE data. The manuscript would rather benefit from a clearer explanation of the importance and novelty of measurements themselves relative to previous work. A brief comparison to Marklund (1984) is provided at the end, but this seems insufficient, unless there has been no significant progress in electric-field

measurements over the past 40 years prior to the BROR experiment.

In the revised manuscript, we will incorporate recent studies to more clearly highlight the significance and novelty of this work.

Using tomography, we tracked the three-dimensional motion of barium clouds with a spatial resolution of 500 m. While the overall characteristics of the electric field are consistent with those reported in previous studies, our method enables a more detailed investigation of the electric field structure and its variations.

L220/ L238 “Figure 13/14”. *How can one interpret the values of this equivalent current in terms of electric field and altitudes? In addition, it would be helpful to show the location of Erange as well as the auroral arc on the map to aid interpretation. Ideally, Figure 14 can be also overlaid there to provide a complete visualising of the results in order to support conclusion of the manuscript.*

Figure 13 shows the height-integrated equivalent current inferred from ground-based magnetometers. It should therefore be interpreted as a regional-scale background current system. In this study, we use it only to check the consistency of the large-scale convection direction with the background drift inferred from the barium cloud motion.

In contrast, Figure 14 shows the electric-field perturbation associated with the auroral arc after subtracting the background convection component.

Thus, Figures 13 and 14 represent different spatial scales: Figure 13 describes the regional background electrodynamic condition, whereas Figure 14 describes the arc-related local structure derived from the barium cloud.

We agree that the spatial relation should be made clearer. In the revised manuscript, we will add the location of Erange and the representative auroral arc position to Figure 13. We will also clarify that Figure 13 represents the regional, height-integrated equivalent current inferred from ground magnetometers, whereas Figure 14 shows the local arc-related electric field in an auroral-arc-relative coordinate system after subtracting the background convection. Because the auroral arc moves with time as shown in Figure R3, directly overlaying the full Figure 14 result on a fixed map would be difficult to interpret; instead, we will improve the figure captions and text to make the relation between the two figures clearer.