

# Fine-scale electric fields and Joule heating from observations of the Aurora

P. Krčelić<sup>1</sup>, R. C. Fear<sup>1</sup>, D. Whiter<sup>1</sup>, B. Lanchester<sup>1</sup>, A. L. Aruliah<sup>2</sup>, M. Lester<sup>3</sup>, L. Paxton<sup>4</sup>

<sup>1</sup>Physics and Astronomy, University of Southampton, Southampton, UK

<sup>2</sup>Atmospheric Physics Laboratory, University College London, Gower Street, London, WC1E 6BT, UK

<sup>3</sup>University of Leicester, Leicester, UK

<sup>4</sup>Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA

## Key Points:

- Small scale electric fields are estimated on both sides of an auroral arc using optical techniques
- Joule heating is estimated, by combining optical data with neutral wind observations.
- Local, high resolution Joule heating shows much higher values than the Joule heating obtained from more averaged radar measurements.

---

Corresponding author: Patrik Krčelić, [P.Krcelic@soton.ac.uk](mailto:P.Krcelic@soton.ac.uk)

## Abstract

Optical measurements from three selected wavelengths have been combined with modelling of emissions from an auroral event to estimate the magnitude and direction of small-scale electric fields on either side of an auroral arc. The temporal resolution of the estimates is 0.1 seconds, which is much higher resolution than measurements from SuperDARN from the same region, with which we compare our estimates. Additionally, we have used the SCANDI instrument to measure the neutral wind during the event in order to calculate the height integrated Joule heating. Joule heating obtained from the small scale electric fields gives larger values ( $17 \pm 11$  and  $6 \pm 9$  mWm<sup>-2</sup> on average on each side of the arc) than the Joule heating obtained from more conventionally used SuperDARN data (4.8 mWm<sup>-2</sup>). This result indicates that high spatial and temporal resolution electric fields may play an important role in the dynamics of the thermosphere, and thus the ionosphere-magnetosphere system in general.

## 1 Introduction

Magnetosphere-ionosphere interactions play a major role in the dynamics of near Earth space which also impact the atmosphere and surface infrastructure. Auroral electric fields are an important link in the magnetosphere-ionosphere interaction, causing Joule heating in the ionosphere (Lanchester et al., 1996), thus acting as a major source of high atmosphere dynamics ( $> 100$  km altitude). Ionospheric feedback also occurs, where the ionosphere plays a significant role in auroral dynamics (Russell et al., 2013). Measurements of the auroral electric fields have been conducted using rocket and satellite measurements (Marklund et al., 1994), incoherent scatter radar measurements (Lanchester et al., 1997; Aikio et al., 2002), coherent scatter radars (Chisham et al., 2007), optical measurements (Tuttle et al., 2014; Dahlgren et al., 2016), or with the combination of two or more measurement techniques, such as a combination of rocket measurements and ground auroral imagery (Clayton et al., 2019). The biggest drawback with direct rocket and satellite measurements is the rapid movement of the instrument, resulting in a good spatial coverage rather than a temporal one. Radar measurements are reliable but have poor spatial and temporal resolution for small-scale electrodynamics. Measured small scale electric fields plus measured local neutral wind can be used to estimate Joule heating (e.g., Billett et al., 2018). Aruliah et al. (2005) investigated JH using 1-min vs 15-min average European incoherent scatter radar (EISCAT) velocities for a common volume tristatic FPI-EISCAT experiment, together with the full neutral wind vector obtained from 3 FabryProt interferometers (FPIs) at Sodankyl, Kiruna and Skibotn. These heating estimates are usually underestimated and a possible explanation for such underestimates could be the highly variable nature of ionospheric electric fields, which is usually missed with radar observations (Deng & Ridley, 2007). The rapid development of technology and modelling techniques in the last decades has resulted in more accurate and more numerous optical studies of the aurora. Dahlgren et al. (2009) first estimated local drift velocities observing afterglow, using the same optical instrument as used in this paper, plus modelling techniques. Auroral emission from O<sup>+</sup> (<sup>2</sup>D-<sup>2</sup>P) at 732.0 nm has a lifetime of approximately 5s, and therefore by combining images of this emission with modelling and images of different prompt emissions, it is possible to determine the O<sup>+</sup> ion velocity and hence electric field. Tuttle et al. (2020) expanded the technique and applied it to observations of a single arc structure.

In the present paper we have expanded the technique of Tuttle et al. (2020) to estimate the small-scale electric fields on either side of an auroral arc. Furthermore, we have used the measured electric fields to estimate the local height integrated Joule heating at subsecond resolution.

## 2 Instruments

### 2.1 ASK

The Auroral Structure and Kinetics instrument (ASK) is a multimono-chromatic imager designed to measure fine-scale structures of the aurora. ASK consists of 3 cameras observing the magnetic zenith, each with a different narrowband filter centered around a selected wavelength. The cameras are labeled as ASK1, ASK2, and ASK3, and are time synchronised. Each camera uses an electron-multiplying charge-coupled device (EMCCD) detector, with 512 x 512 pixels, binned to 256 x 256 to increase the readout speed. An EMCCD is a photosensitive chip which incorporates electron multiplying in order to amplify weak or single photon events above the read noise (Dahlgren et al., 2016). The optical setting is equipped with f/1 lenses with a focal length of 75 mm, resulting in a  $6.2^\circ \times 6.2^\circ$  field of view. Galilean-type converters can be applied to achieve a  $3.1^\circ \times 3.1^\circ$  field of view. In the present event the second camera (ASK2) is observing emission from a higher altitude than the other two cameras, so it was equipped with a converter to reduce the field of view, thereby observing the same field lines as ASK1 and ASK3 without convertors. During the event studied in this work the instrument was observing at a cadence of 20 Hz.

#### 2.1.1 ASK1 - 673 nm

ASK1 has a filter centered on 673 nm with a passband of 14 nm, observing the N<sub>2</sub> 1PG (first positive group)(5,2) and (4,1) band emissions resulting from the excitation of the N<sub>2</sub> molecules by the precipitating electrons (Ashrafi et al., 2009). The N<sub>2</sub> 1PG emissions show little to no dependence on the energy of the precipitating electrons. N<sub>2</sub> emissions are used to estimate the flux of precipitating electrons by dividing the emission in Rayleighs by a coefficient dependent on the precipitating electron energy distribution for the event, as explained in Lanchester et al. (2009). There are no other emissions contaminating the ASK1 channel.

#### 2.1.2 ASK2 - 732 nm

ASK2 observes emissions from the metastable O<sup>+</sup>(<sup>2</sup>P) ion with a 1 nm passband centered on 732 nm. Oxygen ions are produced by the electron precipitation. Rees et al. (1982) showed that 18 % of the total O<sup>+</sup> ionisation results in the O<sup>+</sup>(<sup>2</sup>P) state, which is further divided into two levels of different total angular momentum: the <sup>2</sup>P<sub>1/2</sub> and <sup>2</sup>P<sub>3/2</sub>. In total we have 4 transitions, (<sup>2</sup>P<sub>1/2,3/2</sub> → <sup>2</sup>D<sub>3/2,5/2</sub>), which form 2 doublets (centered on 732 and 733 nm), from which we observe only one doublet with <sup>2</sup>D<sub>5/2</sub> as the lower state. O<sup>+</sup>(<sup>2</sup>P) states are metastable with a lifetime of ≈ 5 s, which allows the auroral features to be tracked and thus estimate the local electric fields (Dahlgren et al., 2009). Peak emission height of metastable O<sup>+</sup>(<sup>2</sup>P) ions is around 250 km. The ASK2 channel is contaminated by OH airglow and the (5, 3) band of N<sub>2</sub> 1PG band system. OH airglow decontamination is achieved by background correction, while for the N<sub>2</sub> 1PG decontamination we use the method described in Spry et al. (2014), where we subtract 2.5% of ASK1 image intensity from ASK2 image.

#### 2.1.3 ASK3 - 777 nm

ASK3 observes emissions caused by a transition between the atomic oxygen <sup>5</sup>P and <sup>5</sup>S states. The ASK3 filter is centered on 777.4 nm and has a passband of 1.5 nm (Lanchester et al., 2009). The 777.4 nm emissions are highly dependent on the energy of the precipitating electrons. Therefore, the ratio between ASK1 and ASK3 brightness can be used to estimate the precipitating electron energy as described in Lanchester et al. (2009). There are no other emissions contaminating the ASK3 channel.

## 2.2 SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) is a network of coherent scatter radars observing the polar cap regions (Chisham et al., 2007). Each radar scans with 16 to 20 beams with each beam scan taking from 3 to 6 seconds, thus resulting in a full radar sweep typically taking 1 or 2 minutes. SuperDARN operates in the high-frequency (HF) range and uses the Doppler shift of radar pulses which are reflected from decametre-scale irregularities in the ionosphere at  $\approx 250$  km height to obtain the line-of-sight (LOS) ion velocities. In this study, we obtain a 2D horizontal convection velocities from a fitting process which constructs potential maps using all radar measurements in a single radar sweep (Ruohoniemi & Baker, 1998). Note that SuperDARN was not designed to look at the horizontal spatial scales that are being investigated in this study; the purpose of using SuperDARN here is to provide an independent estimate of the convection electric field on the larger scale size that is often used in numerical simulations of the high latitude ionosphere.

## 2.3 SCANDI

In order to measure the neutral wind velocities we use the Scanning Doppler Imager (SCANDI) located on Svalbard (Aruliah et al., 2010). SCANDI observes an area with 500 km radius over Svalbard, by dividing it into zones in a way which forms multiple concentric rings. LOS neutral wind velocities are measured in each zone using the Doppler shifts of the 630 nm emission from airglow and aurora. The height of peak 630 nm emission, and thus the neutral wind measurements, is 240–250 km. An averaged 2D neutral wind can be obtained from the LOS velocities in each ring of the imaging area. A full sweep of the SCANDI instrument takes around 7.5 minutes.

## 3 Method

### 3.1 Modelling of metastable emissions

The method of Tuttle et al. (2020) has been used in the present work to model the auroral emissions. Full details can be found in that paper, but a brief description is provided here. Prior to the analysis the magnetic zenith needs to be estimated. This is easily done if auroral rays are present in the event. The orientation of the rays and their intersection are then used to give the position of the magnetic zenith. The model is then applied on a 3D grid with dimensions  $30 \text{ km} \times 30 \text{ km} \times 410 \text{ km}$ . Spatial resolution (both horizontal and vertical) is set to 200 meters and the volume is oriented such that the long axis lies along the magnetic field lines. The process to fill the volume is performed using the following steps. First, the peak energy of precipitating electrons at each pixel is determined using the ratio of the emissions from the images of ASK1 and ASK3 (the two cameras observing prompt emissions). The Southampton ion chemistry model is used (Lanchester et al., 2009), which gives 1D profiles of densities, production and emission of the major species in the Earth’s high altitude atmosphere, with input of the precipitating electron energy distribution, ap and f10.7 indices. A set of profiles is produced by varying the peak energy of the precipitating electron population, but assuming the energy distribution is Gaussian in shape. Each pixel is assigned to a corresponding profile. We then search for the column of a 3D volume where the field of view of a pixel intersects the height of the peak emission from the  $\text{N}_2$  1PG profile of a given pixel. The emission profile is then assigned to a given column in a 3D space. This process is done for each pixel in the image in order to fill a 3D volume. For ASK1 and ASK3 the volume is populated with the  $\text{N}_2$  1PG and atomic oxygen emissions from the ion chemistry model.

For metastable emissions of ASK2 the volume is filled with the  $\text{O}^+2\text{P}$  production rates since in order to calculate the emissions we need to include the horizontal drift ve-

locities in our model.  $O^+(2P)$  emission is proportional to the  $O^+$  density distribution with the continuity equation:

$$\frac{dn}{dt} = q - \sum_k \alpha_k n_k n - \sum_j A_j n - \nabla \cdot (n\vec{v}), \quad (1)$$

where  $n$  is the density of the  $O^+(2P)$  ions,  $q$  is the production rate of the species,  $A_j$  represent the Einstein coefficients,  $\alpha$  represent the quenching rates,  $n_k$  are the densities of the quenching species  $k$ , and  $v$  is a drift velocity. Production rates are obtained from the ion chemistry model as outlined above (Lanchester et al., 2009). The second and third terms on the right hand side of the equation are loss processes due to the quenching and the emissions. Particles are quenched in a collisions with other species. Therefore quenching is greater at regions of increased density (lower altitudes).  $O^+$  is quenched by the electrons, atomic oxygen and molecular nitrogen. Quenching rates for each species have been studied in detail (Stephan et al., 2003; Chang et al., 1993; Rees, 1989). The third term corresponds to the loss due to emission, which is when a particle de-excites and releases a photon. Einstein emission coefficients are obtained from Zeippen (1987). The 732 nm emission line has contributions from  $J_{1/2}$  and  $J_{3/2}$  upper states, which means we have to solve equation 3.1 twice (once for each state). Since the Southampton ion chemistry model gives the production of a whole  $O^+(2P)$  ion species, we use the ratio  $n_{1/2}/n_{3/2} = 0.367$  given in Whiter et al. (2014) to separate the two states. The continuity equation is solved using the method described in Gustavsson et al. (2001). Modelled images are formed from the  $O^+$  density and Einstein coefficients using the blob-based projection method of Rydester and Gustavsson (2000).

The drift velocity in equation 3.1 is treated as a free parameter, which we solve, by minimising the error:

$$err(V) = \sum_{u,v} [I_{obs}(u,v) - I_{mod}(u,v,n(V))]^2. \quad (2)$$

$I_{obs}(u,v)$  is the observed intensity at pixel  $(u,v)$ , where  $u$  and  $v$  are coordinates of the pixel.  $I_{mod}(u,v,n(V))$  is the modelled intensity at pixel  $(u,v)$  from the camera field of view for a given  $O^+$  density  $n(V)$  which is a function of a free velocity parameter  $V$ . We are calculating  $\chi^2$  values in the same manner, with the assumption that each pixel (measurement) has the same variance. From  $\chi^2$  values we are able to calculate confidence intervals and therefore the standard deviations of free parameters. From the estimated drift velocities and the local magnetic field, obtained from IGRF model, the electric fields are calculated using the following equation:

$$\vec{E} = -\vec{v} \times \vec{B} \quad (3)$$

where  $\vec{E}$  represents the electric field,  $\vec{B}$  is the magnetic field and  $\vec{v}$  is drift velocity. We have validated our method by applying it to a synthetically generated auroral feature with given ion velocities. The details of this method and its results are given in Appendix 1A..

### 3.2 Double flow

The above method assumes that there is only one velocity across the field of view of the cameras, whereas observations and theory suggest that the electric field is much more complex in the presence of auroral arcs. The logical next step is therefore to divide the tomographic 3D volume into two parts with different drift velocities. The region dividing the two volumes is called the separatrix and is defined with two param-

eters, angle  $\theta$  and distance  $d$  from the reference point in a tomographic reference plane. Figure 1 shows a schematic representation of the parameters from the view perpendicular to the magnetic field lines. We are assuming that the drift velocities have a common component ( $v_{\perp}$ ) across the arc, and different components ( $v_{\parallel,1}$ ,  $v_{\parallel,2}$ ) along the arc. Such a setup has 5 free parameters:  $\theta$ ,  $d$ ,  $v_{\perp}$ ,  $v_{\parallel,1}$  and  $v_{\parallel,2}$ . In order to reduce the number of parameters and in turn the computing time, we are determining the separatrix parameters ( $\theta$ ,  $d$ ) a priori, using the height integrated O<sup>+</sup>2P production rates. From such images we are able to separate the different auroral structures. The separatrix is determined for each time step, and our model is effectively reduced to only 3 free parameters.

### 3.3 Joule heating estimation

High intensity, short period electric fields obtained from our model are the main contributor to the differences in the local and global heating rates. One of the main goals of the research is to estimate the Joule heating profile, but for that we need the height profiles of both the neutral wind velocity and Pedersen conductivities. Obtaining such profiles is challenging, and therefore we make the following simplifying assumptions. We calculate the height integrated Joule heating ( $\sum Q_J$ ) and the height integrated Pedersen conductivity ( $\sum \sigma_P$ ). It should be noted, that we did not do the height integration but used the empirical formula for height integrated Pedersen conductivity, which assumes integration over the whole column. Electric fields obtained from modelling of the O<sup>+</sup>(<sup>2</sup>P) ions is assumed to be constant across the height profile due to the assumption of straight, non-diverging magnetic fieldlines in area of observation. We also assume that the average neutral wind ( $\vec{v}_N$ ) is represented by the neutral wind measurements obtained from the SCANDI instrument. This is a weak assumption since neutral wind changes significantly with height, but as it will be presented in further sections, neutral wind plays a minor role in local, near auroral Joule heating due to the strong and highly variable electric fields. In order to estimate a height integrated Joule heating we use equation (e.g., Billett et al., 2018; Baker et al., 2004):

$$\sum Q_J = \sum \sigma_P E^2 + 2 \sum \sigma_P \vec{E} \cdot (\vec{v}_N \times \vec{B}) + \sum \sigma_P (\vec{v}_N \times \vec{B})^2, \quad (4)$$

where  $\sum Q_J$  represents the height integrated Joule heating,  $\sum \sigma_P$  height integrated Pedersen conductivity, and  $\vec{v}_N$  neutral wind velocity.  $\vec{E}$  and  $\vec{B}$  are the electric and magnetic fields respectively. The height integrated Pedersen conductivity is estimated using the equations for solar Pedersen conductivity from Rich et al. (1987) and auroral Pedersen conductivity from Robinson et al. (1987). Total Pedersen conductivity is calculated as:

$$\sum \sigma_P = \sqrt{\sum \sigma_{P,A}^2 + \sum \sigma_{P,S}^2}, \quad (5)$$

where  $\sum \sigma_{P,A}^2$  and  $\sum \sigma_{P,S}^2$  are auroral and solar Pedersen conductivities respectively.

## 4 Data and Results

For our analysis we are using an event from 21 December, 2014. We have analysed 4 seconds of the increased auroral dynamics centred around the time 22:47:45 UT. During this event IMF  $B_z$  was positive and had a value of 3.25 nT, IMF  $B_y$  was 10.52 nT and AE index was 444 nT.

Figure 2 shows the Defense Meteorological Satellite Program (DMSP) F16 satellite image of the aurora from observations of Special Sensor Ultraviolet Spectrographic Imager (SSUSI) Lyman-Birge-Hopfield-short (LBH-S) emission. Although the satellite image does not cover Svalbard, the F16 image is the closest available both temporally

and spatially to our event. From the location of the auroral zone seen in Fig. 2, and the fact that we have observed an auroral arc over Svalbard, we can claim with confidence that Svalbard was at the poleward edge of the auroral zone at the time of our observation. The SSUSI images show blurred aurora, while the ASK images show a clear and sharp arc. The reason for this difference lays in both the temporal and spatial resolutions of the two instruments. Since SSUSI images a wider area and samples over a longer time period, rapidly moving small scale auroral features seem blurred, while ASK can clearly distinguish such features.

Figure 3 shows the time evolution of our event seen from all three ASK cameras. The black squares on the images for the two prompt emissions (ASK1 and ASK3) represent the field of view of the ASK2 camera. The time evolution of the metastable emissions during the event can be seen in the second row of figure 3. In the second and third panels the detachment of two auroral features is marked with arrows. In the fourth panel the auroral features have reattached into a single arc. The video showing the evolution of the auroral arc in all three cameras, same as in figure 3 is given in supplementary material under the name movie\_01.gif.

Figure 4 shows the results of the double flow model. The upper row shows the observed metastable emission images, while the bottom row shows the modelled metastable emission images. Each column matches the four times shown in figure 3. The contours in the top panels indicate the upper 95 % brightness in the corresponding lower panels. Comparison of the contours with the background image in the top row shows that the modelled and observed metastable emissions match well. The video showing the comparison between modelled and observed ASK2 images is given in supplementary material under the name movie\_02.gif.

Velocities estimated from the model are shown in figure 5, and the corresponding electric fields obtained from these velocities are shown in figure 6. Values in figures 5 and 6 represent the magnitudes of the given vectors, while the sign corresponds to the sign of the x-axis component of each vector. On the north side of the auroral arc, electric fields are oriented towards the east direction, while on the south side of the auroral arc, the electric fields are oriented towards the south-east direction. Both sides of the arc show dynamic behaviour, with a clear shear between them.

During the time of the event there were no direct SuperDARN measurements over Svalbard so we used the fitting technique from Ruohoniemi and Baker (1998) to obtain a potential map from which we have calculated the background convection velocity. We have chosen to use an 8th order spherical harmonic fit to the convection pattern, which provides a better agreement (not shown) between the 'fitted' vectors which result from the map potential technique, and the 'true' vectors, which combine the measured line of sight [LOS] velocity components with the components of the fitted vectors that are transverse to the line of sight direction. Figure 7 shows the potential map with SuperDARN fitted vectors. The location of Svalbard is indicated by a black rectangle. Although there is no scatter over Svalbard at this time, we have plotted a "fitted" vector, which is calculated from the map potential data at the location of the ASK imager, for later comparison. This is the vector plotted with the larger circle, which lies within the black box. The estimated velocity of the fitted flow at this point is 412 m/s.

The neutral wind velocity obtained from the SCANDI instrument was 169.5 m/s mostly in the southern direction. Figures 8 and 9 show all velocities in geographic coordinates from the southern and northern sides of the arc, respectively. Blue vectors are the drift velocities obtained from our model, the red vector is the drift velocity from SuperDARN, and the black vector is the neutral wind. Figure 8 shows velocities from the southern side of the arc, while figure 9 shows velocities from the northern side of the arc. Note, there is a difference in scale on both x and y axes between the two figures.



**Table 1.** Results of double-flow (marked DF) model, in comparison with the results from SuperDARN.  $\bar{E}$  is the average value of electric field, while  $E_{MAX}$  is the maximum value in the observed interval. Using the same notation  $\overline{\sum Q}$  is the average and  $\sum Q_{MAX}$  is the maximum value of height integrated Joule heating.  $En$  indicates the energy transferred to the atmosphere during our interval, and is obtained by integrating the Joule heating rate over the 4 s duration of the observations.

	$\bar{E}$ [mVm <sup>-1</sup> ]	$E_{MAX}$ [mVm <sup>-1</sup> ]	$\overline{\sum Q}$ [mWm <sup>-2</sup> ]	$\sum Q_{MAX}$ [mWm <sup>-2</sup> ]	$En$ [mJm <sup>-2</sup> ]
DF north	53 ± 15	88 ± 16	17 ± 11	46 ± 18	59 ± 22
DF south	36 ± 17	66 ± 21	6 ± 9	26 ± 19	24 ± 18
SuperDARN	20.2		4.8		17.1

Figure 10 depicts the estimated Joule heating on both sides of the arc using equation (4). The black line in figure 10 represents the height integrated Joule heating using the estimated SuperDARN velocity. Here we can see the differences between Joule heating obtained from local time varying electric fields obtained from our method and Joule heating obtained from more averaged estimated SuperDARN velocity.

Table 1 summarises the results obtained in this paper.

## 5 Discussion

Small scale electric fields have proven crucial in the estimation of Joule heating in the thermosphere. Using the described method we have obtained the electric fields with temporal resolution of 0.1 seconds and thus have been able to resolve the motion of two auroral features within a single auroral arc. The SuperDARN potential map in Figure 7 indicates complex ionospheric convection during our event. The potential maps were calculated using the full sweep of the SuperDARN radars which took around 1 minute. In the absence of any data over Svalbard, the estimates from SuperDARN are a combination of the effect of the observations to the south and west of Svalbard, and the model potential pattern used for the analysis. As mentioned in Section 2.2, SuperDARN was not designed to make observations on the horizontal spatial scales that are measured by ASK. The purpose of this research is to highlight the importance of the sub-grid physics, which need to be considered in modelling of auroral regions. The electric fields obtained from optical measurements and modelling are from a 4 second interval, in which an auroral arc passed through the ASK camera view. We are treating electric fields from camera measurements as local electric fields related to the auroral dynamics. Our estimated local drift velocities near the auroral arc (0.3-1.5 km/s) are in agreement with the previous study of Tuttle et al. (2020), who estimated drift velocities around an auroral arc to be varying from 0.4 to 1.2 km/s with peak drift velocity of 2.4 km/s, but their estimate represented a spatial average across the entire field of view. Electric fields are highly variable, varying in both direction and intensity. Figure 11 shows drift velocities and electric fields in relation to the auroral arc at 22:47:46.1 UT. The image is from the ASK1 camera (N<sub>2</sub> 1PG emission), and vectors are placed at the center of mass of the traced feature intensity. The black dashed line is the position of the separatrix at 132 km which is the average N<sub>2</sub> 1PG peak emission height for our event. The average electric fields of both features are oriented in the general direction of the arc movement, but in their time evolution electric fields often have different orientation and intensity compared to each other.



By further use of the estimated electric fields we are able to estimate the height integrated Joule heating, while comparing it to a more conventional estimate of the Joule heating based on SuperDARN data. Our Joule heating estimated from small scale electric fields has a peak value of  $46 \pm 18$  mW/m<sup>2</sup> and mean value of  $17 \pm 11$  mW/m<sup>2</sup> for the region north of the auroral arc and a peak value of  $26 \pm 19$  mW/m<sup>2</sup> and mean value of  $6 \pm 9$  mW/m<sup>2</sup> for the region south of the auroral arc. The Joule heating estimated from our optical method shows magnitudes up to 6 times larger on the northern side of the auroral arc and roughly the same values on the southern side of the auroral arc, compared to ones estimated from lower resolution SuperDARN data. The height integrated Joule heating obtained from SuperDARN is 4.8 mW/m<sup>2</sup>, which is in agreement with previous estimates. Baker et al. (2004) used SuperDARN data with the TIMED spacecraft to obtain heating rates, and estimated peak Joule heating of around 40 mW/m<sup>2</sup> on the dusk side of the auroral oval with the values at the edge of the auroral zone close to or below 10 mW/m<sup>2</sup>. Weimer (2005) used hybrid field aligned currents and electric potential models to estimate northern hemisphere Joule heating for various geomagnetic conditions. For geomagnetic conditions similar to those in this paper Weimer (2005) obtained peak auroral zone Joule heating around 7 mW/m<sup>2</sup> and 4 mW/m<sup>2</sup> at the poleward edge of the auroral zone. The highest Joule heating values from Weimer (2005) were obtained for southward IMF with peak auroral zone Joule heating around 18 mW/m<sup>2</sup> and 8 mW/m<sup>2</sup> at the poleward edge of the auroral zone.

The importance of local Joule heating is also highlighted by Kiene et al. (2019) who combined SuperDARN and Poker Flat Incoherent Scatter Radar (PFISR) to estimate Joule heating and showed the difference of local hotspots and background Joule heating to be a factor of 10. In their paper Kiene et al. (2019) have also shown that the Joule heating is reduced by a factor of 3 with inclusion of neutral wind once it is oriented in the same direction as the convection velocity. A similar conclusion was given by Billett et al. (2020), who estimated that the Joule heating is reduced to near zero when the neutral wind has the same orientation as the convection velocity. Our results suggest that the importance of small scale electric fields is even greater, since the local electric fields can be more intense and are often in a different direction from the bulk electric field caused by the convection. Furthermore, because of the highly dynamic nature of the small-scale electric fields, the neutral wind will not re-orient itself towards the local ion motion but will stay in the same orientation as the bulk flow, resulting in a high intensity local Joule heating (although of short duration). Such significant differences between the local and global estimates indicate the important role of the local Joule heating in the overall dynamics of the thermosphere.

## 6 Conclusions

Using the ASK instrument and Southampton ion chemistry model we have obtained small-scale electric fields on each side of an auroral arc for an event at 22:47:45 UT on 21 December 2014. Obtained electric fields have subsecond resolution and peak value of  $88 \pm 16$  mVm<sup>-1</sup> on the northern side of the arc and peak value of  $66 \pm 21$  mVm<sup>-1</sup> on the southern side of the arc. Using small scale electric fields and the SCANDI instrument we have calculated the local height integrated Joule heating. Joule heating heating obtained from small scale electric fields gives much larger values than that obtained from SuperDARN data. We conclude that with high resolution electric fields we can obtain more accurate (larger) estimates of Joule heating which are usually missed with more averaged radar measurements. Therefore, small-scale electric fields play a large role in local, highly intense heating and most likely in overall heating of the ionosphere.

Our optical method for estimating electric fields, and consequently the Joule heating using ASK has proven to be very valuable in understanding the local heating effects in the vicinity of auroral activity. The method is quite complex, requiring certain conditions to work, such as strong O<sup>+</sup> (<sup>2</sup>P) aurora, clear sky and correct estimation of mag-

netic zenith. The main goal of further research will be to extend the method to more complicated cases as well as analysing a wide range of events to reach more general conclusions on local Joule heating and its role in large scale dynamics of the upper atmosphere.

## Appendix A Ion drift optical method validation using synthetic auroral feature

In order to verify our method we have created a synthetic feature with given ion drift velocities. We have assumed a simple auroral feature with circular cross-section in the vertical plane with 2 km diameter and precipitating electron energy of 700 eV. The flux of precipitating electrons was  $6 \text{ mWm}^{-2}$  in the innermost 400 m of the feature and  $4 \text{ mWm}^{-2}$  throughout the rest of the feature. We have made multiple cases of synthetic spectra. Firstly we have divided our synthetics between those with single frame precipitation (a flash-like auroral feature) and those with continuous precipitation throughout the whole event. Secondly we have added the precipitation source movement which is seen in our volume as movement with velocity of 2 km/s. The source velocity (both magnitude and direction) was kept constant throughout each individual synthetic event, but was different for each event. Finally we have added the single ion drifts across the field of view (single flow case, with x and y components), in a way that the drift velocity increases from 0 to 1.3 km/s with each step and decreases back to zero in a single direction (eg. x direction). The same drift then occurs in the perpendicular direction (eg. y direction). We have increased the number of cases by switching the initial direction of the drift velocity.

We have then run our model on synthetic auroral features in order to retrieve the drift velocities and compare them with those included synthetically. Since all cases gave similar results we will only present one case. Figure A1 shows the evolution of the synthetic auroral feature in this case, which corresponds to an event for which the precipitation was continuous and the source movement changed. Each panel depicts the time after the start of precipitation shown above each panel. The video showing the evolution of synthetic auroral feature is given in supplementary material under the name movie\_ap01.gif.

Figure A2 show the comparison between retrieved drift velocities represented by the red line and initial drift velocities represented by the black line. The red dashed line represent the standard deviations of retrieved drift velocities. The upper panel of figure A2 depicts the x direction of velocities, while the lower panel depicts the y direction. As seen from both figures, the retrieved velocities match well except for initial 0.5 seconds, during which time the model corrects and adjusts for the initial conditions. Such behaviour is seen in all cases, and therefore we have cut the initial 0.5 from all results presented in this paper.

## Acknowledgments

The ASK instrument has been funded by PPARC, STFC and NERC of the UK and by the Swedish Research Council. The UCL Scanning Doppler Imager (SCANDI) is maintained thanks to Dr. Ian McWhirter. SuperDARN is funded by national scientific funding agencies of Australia, Canada, China, France, Japan, South Africa, the UK and the USA. The SuperDARN convection modeling was performed using RST4.1 (<https://github.com/SuperDARN/rst>).

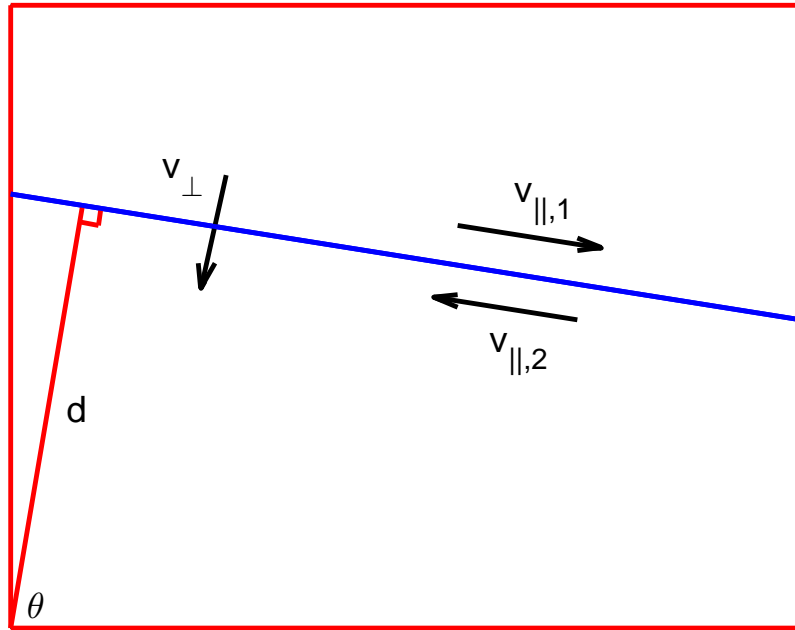
PK was supported by NERC INSPIRE studentship NE/S007210/1. RCF was supported by STFC consolidated grant ST/R000719/1. DKW was supported by NERC Independent Research Fellowship NE/S015167/1. ALA was supported by NERC grants NE/N004051/1 and NE/W003112/1.

## References

- Aikio, A. T., Lakkala, T., Kozlovsky, A., & Williams, P. J. S. (2002). Electric fields and currents of stable drifting auroral arcs in the evening sector. *Journal of Geophysical Research: Space Physics*, 107(A12), SIA 3-1-SIA 3-14. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JA009172> doi: <https://doi.org/10.1029/2001JA009172>
- Aruliah, A. L., Griffin, E. M., Aylward, A. D., Ford, E. A. K., Kosch, M. J., Davis, C. J., ... Jussila, J. (2005). First direct evidence of meso-scale variability on ion-neutral dynamics using co-located tristatic fpis and eiscat radar in northern scandinavia. *Annales Geophysicae*, 23(1), 147–162. Retrieved from <https://angeo.copernicus.org/articles/23/147/2005/> doi: 10.5194/angeo-23-147-2005
- Aruliah, A. L., Griffin, E. M., Yiu, H.-C. I., McWhirter, I., & Charalambous, A. (2010). Scandi-an all-sky doppler imager for studies of thermospheric spatial structure. *Annales Geophysicae*, 28(2), 549–567. Retrieved from <https://angeo.copernicus.org/articles/28/549/2010/> doi: 10.5194/angeo-28-549-2010
- Baker, J. B. H., Zhang, Y., Greenwald, R. A., Paxton, L. J., & Morrison, D. (2004). Height-integrated joule and auroral particle heating in the night side high latitude thermosphere. *Geophysical Research Letters*, 31(9). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004GL019535> doi: <https://doi.org/10.1029/2004GL019535>
- Billett, D. D., Grocott, A., Wild, J. A., Walach, M.-T., & Kosch, M. J. (2018). Diurnal variations in global joule heating morphology and magnitude due to neutral winds. *Journal of Geophysical Research: Space Physics*, 123(3), 2398–2411. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JA025141> doi: <https://doi.org/10.1002/2017JA025141>
- Billett, D. D., Hosokawa, K., Grocott, A., Wild, J. A., Aruliah, A. L., Ogawa, Y., ... Lester, M. (2020). Multi-instrument observations of ion-neutral coupling in the dayside cusp. *Geophysical Research Letters*, 47(4), e2019GL085590. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL085590> (e2019GL085590 10.1029/2019GL085590) doi: <https://doi.org/10.1029/2019GL085590>
- Chang, T., Torr, D. G., Richards, P. G., & Solomon, S. C. (1993). Reevaluation of the  $\text{o}^+(\text{p})$  reaction rate coefficients derived from atmosphere explorer c observations. *Journal of Geophysical Research: Space Physics*, 98(A9), 15589–15597. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/93JA00957> doi: <https://doi.org/10.1029/93JA00957>
- Chisham, G., Lester, M., Milan, S., Freeman, M., Bristow, W., Grocott, A., ... others (2007). A decade of the super dual auroral radar network (superdarn): Scientific achievements, new techniques and future directions. *Surveys in geophysics*, 28(1), 33–109.
- Clayton, R., Lynch, K., Zettergren, M., Burleigh, M., Conde, M., Grubbs, G., ... Varney, R. (2019). Two-dimensional maps of in situ ionospheric plasma flow data near auroral arcs using auroral imagery. *Journal of Geophysical Research: Space Physics*, 124(4), 3036–3056. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JA026440> doi: <https://doi.org/10.1029/2018JA026440>
- Dahlgren, H., Ivchenko, N., Lanchester, B., Ashrafi, M., Whiter, D., Marklund, G., & Sullivan, J. (2009). First direct optical observations of plasma flows using afterglow of  $\text{o}^+$  in discrete aurora. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71(2), 228–238. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1364682608003751> doi: <https://doi.org/10.1016/j.jastp.2008.11.015>
- Dahlgren, H., Lanchester, B. S., Ivchenko, N., & Whiter, D. K. (2016). Electro-

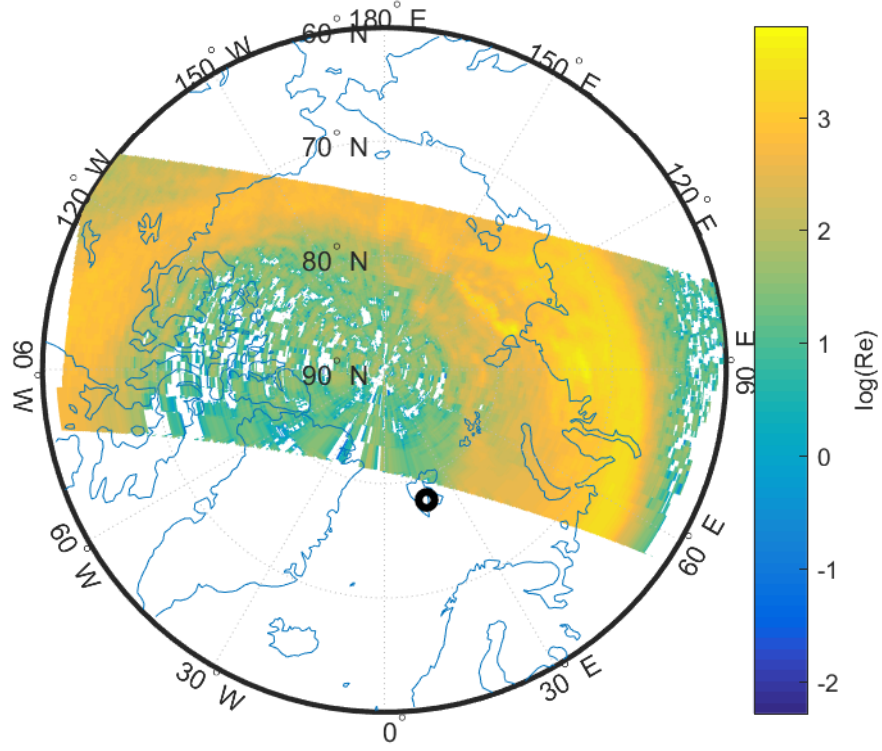
- dynamics and energy characteristics of aurora at high resolution by optical methods. *Journal of Geophysical Research: Space Physics*, 121(6), 5966-5974. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JA022446> doi: <https://doi.org/10.1002/2016JA022446>
- Deng, Y., & Ridley, A. J. (2007). Possible reasons for underestimating joule heating in global models: E field variability, spatial resolution, and vertical velocity. *Journal of Geophysical Research: Space Physics*, 112(A9). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JA012006> doi: <https://doi.org/10.1029/2006JA012006>
- Gustavsson, B., Sergienko, T., Rietveld, M. T., Honary, F., Steen, A., Brndstrm, B. U. E., ... Marple, S. (2001). First tomographic estimate of volume distribution of hf-pump enhanced airglow emission. *Journal of Geophysical Research: Space Physics*, 106(A12), 29105-29123. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000JA900167> doi: <https://doi.org/10.1029/2000JA900167>
- Kiene, A., Bristow, W. A., Conde, M. G., & Hampton, D. L. (2019). High-resolution local measurements of f region ion temperatures and joule heating rates using superdarn and ground-based optics. *Journal of Geophysical Research: Space Physics*, 124(1), 557-572. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JA025997> doi: <https://doi.org/10.1029/2018JA025997>
- Lanchester, B. S., Ashrafi, M., & Ivchenko, N. (2009). Simultaneous imaging of aurora on small scale in oi (777.4 nm) and n<sub>2</sub>1p to estimate energy and flux of precipitation. *Annales Geophysicae*, 27(7), 2881-2891. Retrieved from <https://angeo.copernicus.org/articles/27/2881/2009/> doi: [10.5194/angeo-27-2881-2009](https://doi.org/10.5194/angeo-27-2881-2009)
- Lanchester, B. S., Kaila, K., & McCrea, I. W. (1996). Relationship between large horizontal electric fields and auroral arc elements. *Journal of Geophysical Research: Space Physics*, 101(A3), 5075-5084. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/95JA02055> doi: <https://doi.org/10.1029/95JA02055>
- Lanchester, B. S., Rees, M. H., Lummerzheim, D., Otto, A., Frey, H. U., & Kaila, K. U. (1997). Large fluxes of auroral electrons in filaments of 100 m width. *Journal of Geophysical Research: Space Physics*, 102(A5), 9741-9748. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/97JA00231> doi: <https://doi.org/10.1029/97JA00231>
- Marklund, G., Blomberg, L., Flthammar, C.-G., & Lindqvist, P.-A. (1994). On intense diverging electric fields associated with black aurora. *Geophysical Research Letters*, 21(17), 1859-1862. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/94GL00194> doi: <https://doi.org/10.1029/94GL00194>
- Rees, M. H. (1989). *Physics and chemistry of the upper atmosphere*. Cambridge University Press.
- Rees, M. H., Abreu, V. J., & Hays, P. B. (1982). The production efficiency of o+(p) ions by auroral electron impact ionization. *Journal of Geophysical Research: Space Physics*, 87(A5), 3612-3616. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JA087iA05p03612> doi: <https://doi.org/10.1029/JA087iA05p03612>
- Rich, F. J., Gussenhoven, M. S., & Greenspan, M. E. (1987, December). Using simultaneous particle and field observations on a low altitude satellite to estimate Joule heat energy flow into the high latitude ionosphere. *Annales Geophysicae*, 5, 527-534.
- Robinson, R. M., Vondrak, R. R., Miller, K., Dabbs, T., & Hardy, D. (1987). On calculating ionospheric conductances from the flux and energy of precipitating electrons. *Journal of Geophysical Research: Space Physics*, 92(A3), 2565-

2569. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JA092iA03p02565> doi: <https://doi.org/10.1029/JA092iA03p02565>
- Ruohoniemi, J. M., & Baker, K. B. (1998). Large-scale imaging of high-latitude convection with super dual auroral radar network hf radar observations. *Journal of Geophysical Research: Space Physics*, 103(A9), 20797-20811. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/98JA01288> doi: <https://doi.org/10.1029/98JA01288>
- Russell, A. J. B., Wright, A. N., & Streltsov, A. V. (2013). Production of small-scale alfvén waves by ionospheric depletion, nonlinear magnetosphere-ionosphere coupling and phase mixing. *Journal of Geophysical Research: Space Physics*, 118(4), 1450-1460. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgra.50168> doi: <https://doi.org/10.1002/jgra.50168>
- Rydsten, P., & Gustavsson, B. (2000). Investigation of smooth basis functions and an approximated projection algorithm for faster tomography. *International Journal of Imaging Systems and Technology*, 11(6), 347-354. Retrieved from <https://onlinelibrary.wiley.com/doi/abs/10.1002/ima.1019> doi: <https://doi.org/10.1002/ima.1019>
- Spry, J., Jokiahio, O., Lanchester, B., & Whiter, D. (2014). Modelling n21p contamination in auroral o+ emissions. *Journal of Atmospheric and Solar-Terrestrial Physics*, 107, 8-11. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1364682613002848> doi: <https://doi.org/10.1016/j.jastp.2013.10.013>
- Stephan, A. W., Meier, R. R., Dymond, K. F., Budzien, S. A., & McCoy, R. P. (2003). Quenching rate coefficients for o+(2p) derived from middle ultraviolet airglow. *Journal of Geophysical Research: Space Physics*, 108(A1). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JA009540> doi: <https://doi.org/10.1029/2002JA009540>
- Tuttle, S., Gustavsson, B., & Lanchester, B. (2014). Temporal and spatial evolution of auroral electron energy spectra in a region surrounding the magnetic zenith. *Journal of Geophysical Research: Space Physics*, 119(3), 2318-2327. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JA019627> doi: <https://doi.org/10.1002/2013JA019627>
- Tuttle, S., Lanchester, B., Gustavsson, B., Whiter, D., Ivchenko, N., Fear, R., & Lester, M. (2020). Horizontal electric fields from flow of auroral o+(2p) ions at sub-second temporal resolution. *Annales Geophysicae*, 38(4), 845-859. Retrieved from <https://angeo.copernicus.org/articles/38/845/2020/> doi: [10.5194/angeo-38-845-2020](https://doi.org/10.5194/angeo-38-845-2020)
- Weimer, D. R. (2005). Improved ionospheric electrodynamic models and application to calculating joule heating rates. *Journal of Geophysical Research: Space Physics*, 110(A5). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JA010884> doi: <https://doi.org/10.1029/2004JA010884>
- Whiter, D. K., Lanchester, B. S., Gustavsson, B., Jallo, N. I. B., Jokiahio, O., Ivchenko, N., & Dahlgren, H. (2014, nov). Relative brightness of the o+(2d-2p) doublets in low-energy aurorae. *The Astrophysical Journal*, 797(1), 64. Retrieved from <https://doi.org/10.1088/0004-637x/797/1/64> doi: [10.1088/0004-637x/797/1/64](https://doi.org/10.1088/0004-637x/797/1/64)
- Zeippen, C. (1987). Improved radiative transition probabilities for o ii forbidden lines. *Astronomy and Astrophysics*, 173, 410-414.



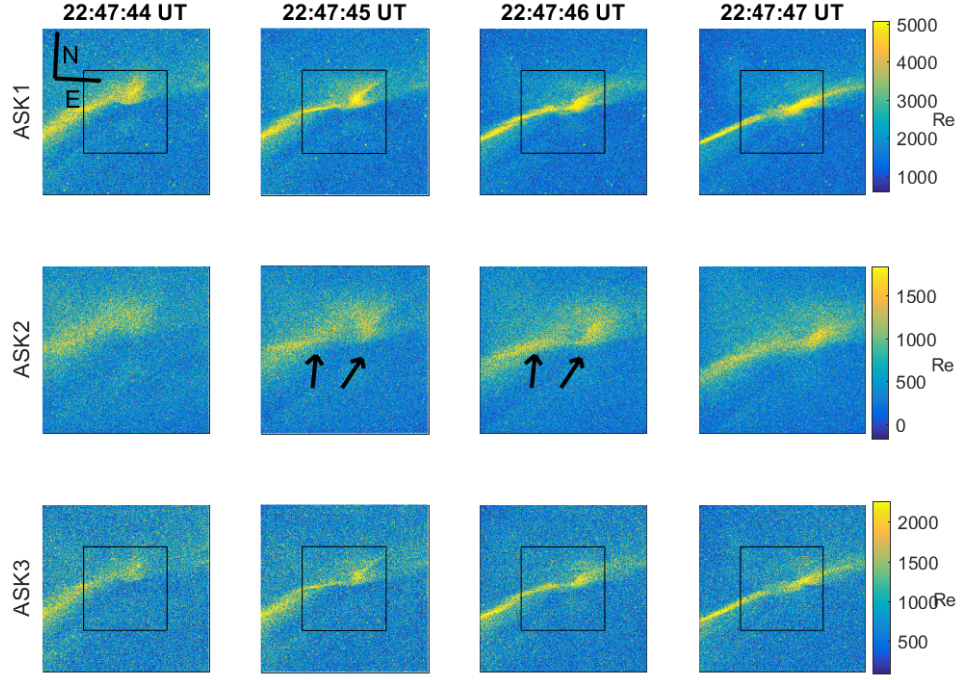
**Figure 1.** Schematic representation of model parameters, from top view of tomographic volume. The blue line represents the separatrix, while black vectors represent velocities.  $\theta$ ,  $d$  are separatrix parameters and,  $v_{\perp}$ ,  $v_{\parallel,1}$ ,  $v_{\parallel,2}$  are given velocities.



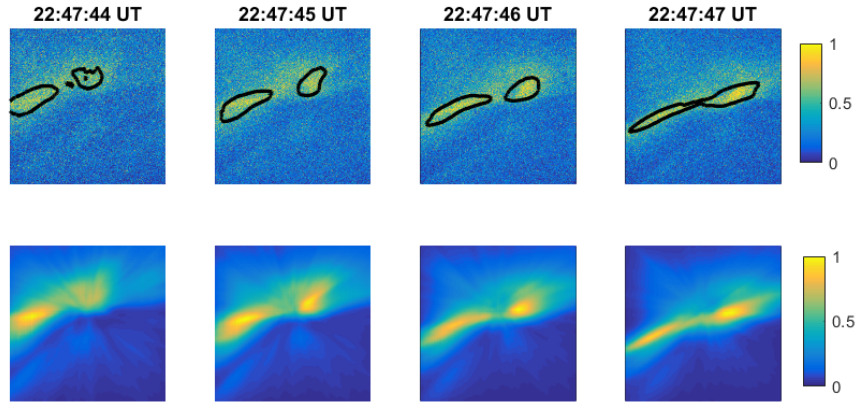


**Figure 2.** Auroral LBH-S emission seen from DMSP F16 spacecraft cut in time between 23:15:18 and 23:31:25 UT on 21 December 2014. Results are given in geographical coordinates and the location of Svalbard is indicated with a black circle.

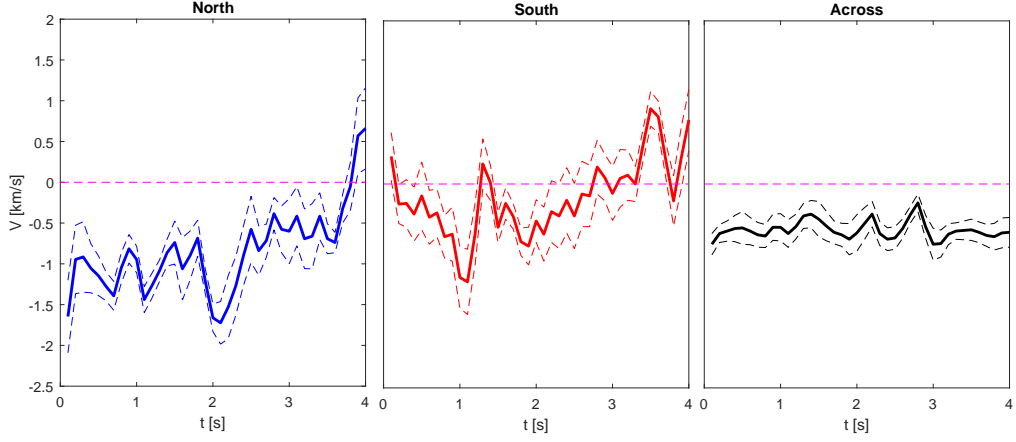




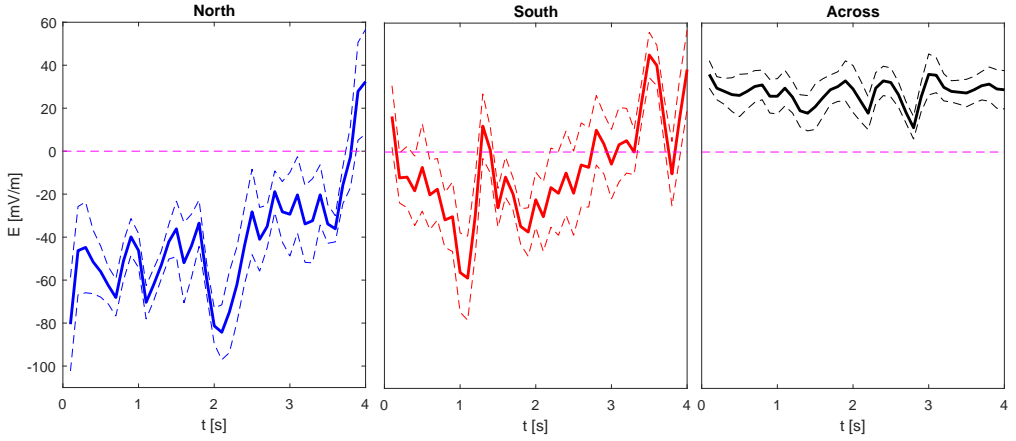
**Figure 3.** Evolution of the auroral features on 21 December, 2014, as seen from the three ASK cameras. Rows indicate the ASK camera number, while columns indicate the times of images labeled above. ASK1 and ASK3 are cameras observing two prompt emissions. ASK2 is the camera observing metastable emission. During this event a telescope was present on ASK2 so the black rectangles on the ASK1 and ASK3 images represent the field of view of ASK2.



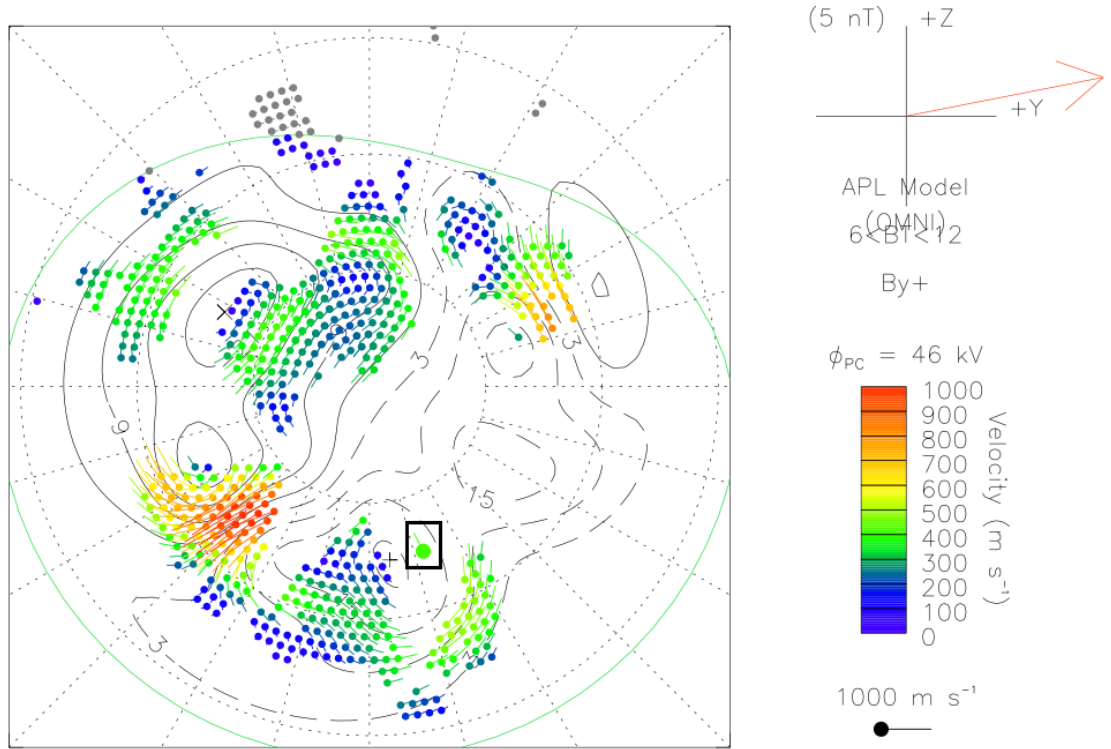
**Figure 4.** Comparison between modelled and observed images of metastable  $O^+$ . Top row shows observed and bottom row modelled images. Contours on the observed images represent the 95% level of the modelled brightness. Time in UT is indicated on top of each column.



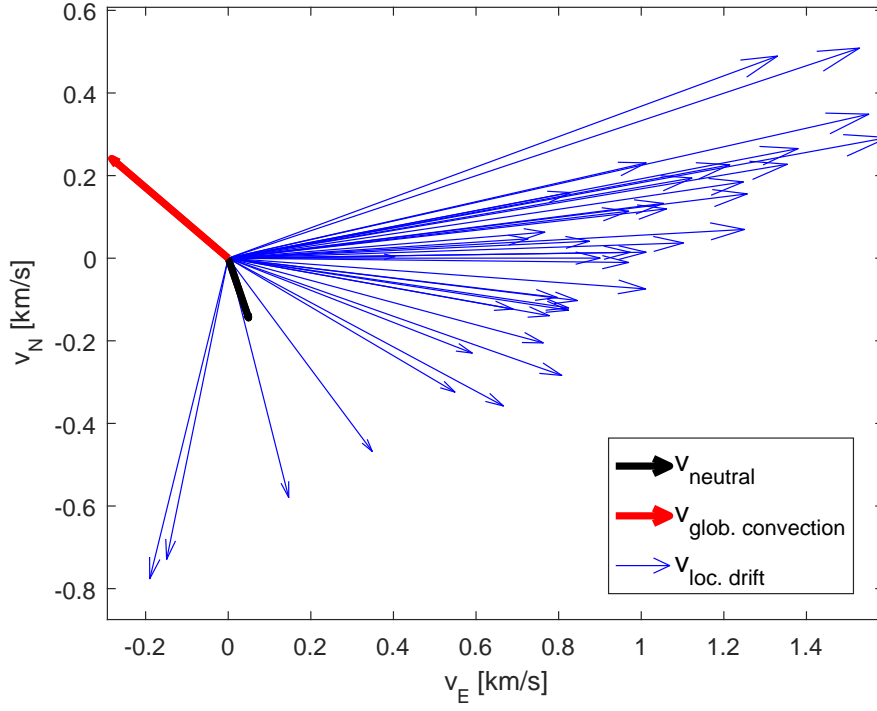
**Figure 5.** Modelled velocities for each time step. The blue line represents northern parallel velocity, the red line represents southern parallel velocity and the black line represents velocity across the arc. Dashed lines represent standard deviations.



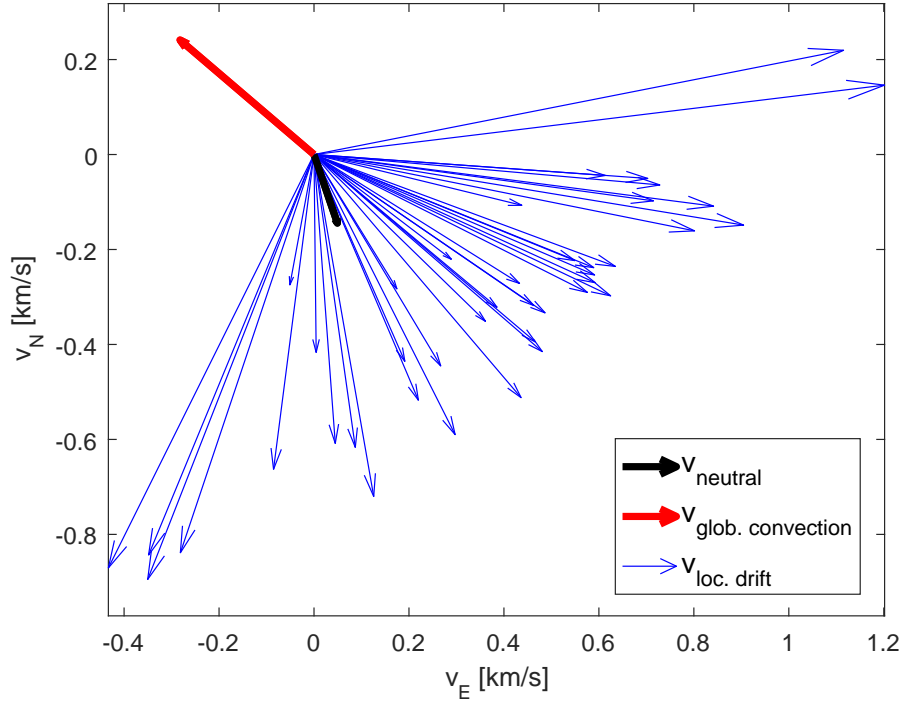
**Figure 6.** Modelled electric fields for each time step. Line colours are the same as in figure 5.



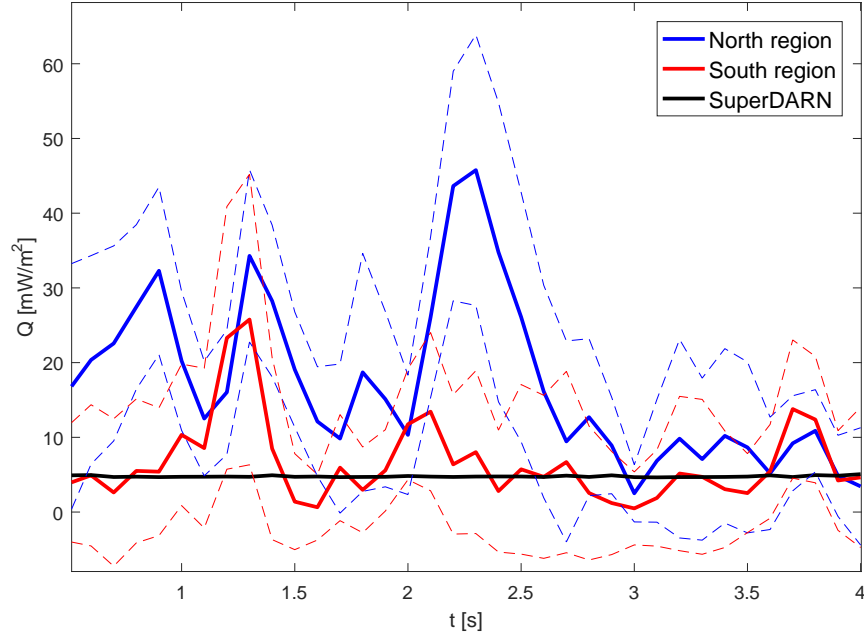
**Figure 7.** The SuperDARN fitted vectors and contours. The Svalbard location is indicated with a black rectangle.



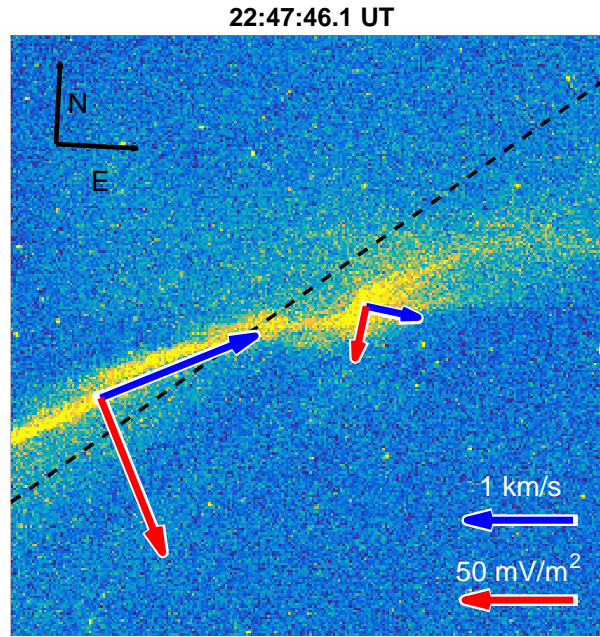
**Figure 8.** Velocities in the area north of the auroral arc shown in geographic system. Blue vectors represent the drift velocities from optical measurements north of the auroral arc, the red vector represents convection from SuperDARN and the black vector represents the neutral wind obtained from SCANDI.



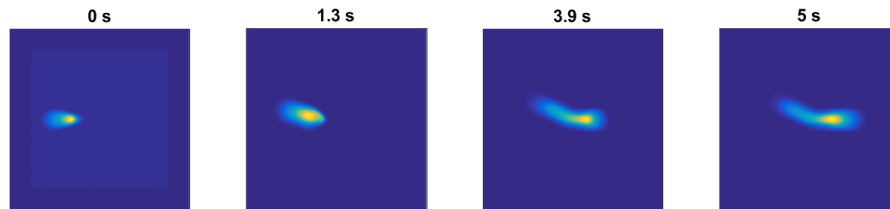
**Figure 9.** Velocities in the area south of the auroral arc shown in geographic system. Blue vectors represents drift velocities from optical measurements south of the arc. The rest of the vectors are the same as in figure 8.



**Figure 10.** Height integrated Joule heating from both sides of the arc compared with SuperDARN estimates. The red line represents Joule heating south of the auroral arc, the blue line represents Joule heating south of the auroral arc and the black line represents Joule heating obtained from SuperDARN measurements.

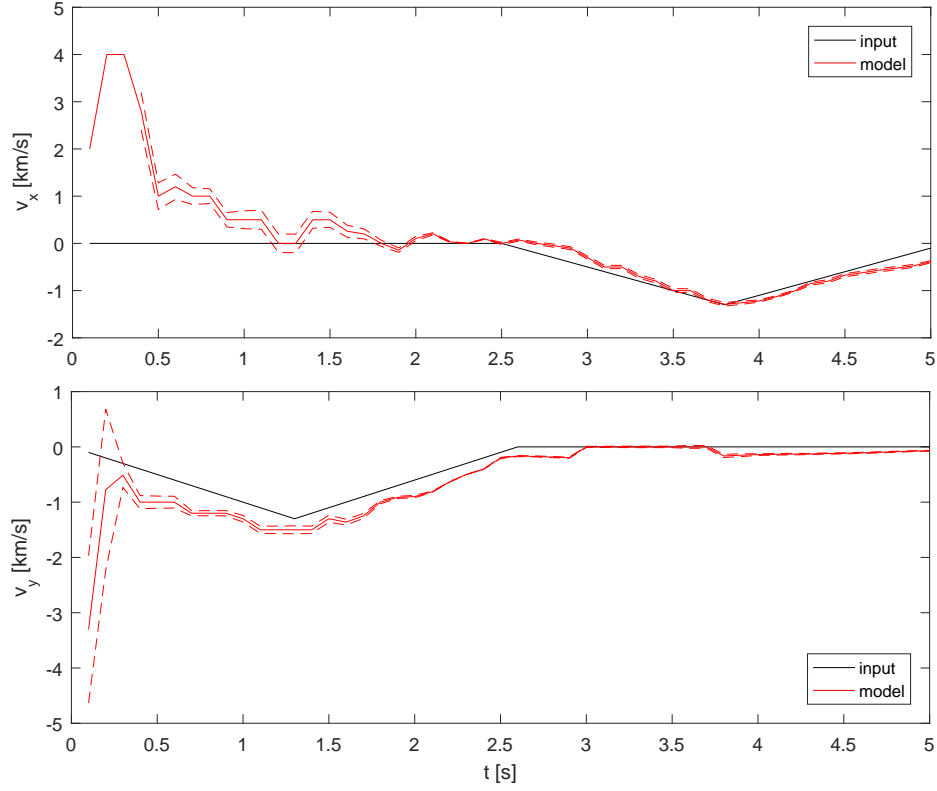


**Figure 11.** Estimated drifts and electric fields in relation with observed auroral arc. The blue vectors represent drift velocities, the red vectors represent electric field, and black dashed line represent separatrix at 132 km altitude. Vector scales are given in the lower right corner of the panel.



**Figure A1.** Evolution of synthetic auroral feature. Each panel depicts different timesteps labeled above each panel.





**Figure A2.** Comparison between input synthetic velocities, labeled with the black line and retrieved velocities from our method, labeled with the red line. Red dotted lines represent standard deviations of estimates. Upper panel depicts the x component of velocity vectors, while bottom panel depicts y component of velocity vectors.