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Dense Array Imaging SYstem prototype observations of missing auroral scale sizes

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Abstract. This paper gives an overview of the Canadian Dense Array Imaging SYstem (DAISY) and its prototype data. The Dense Array is designed to work as campaign instrumentation and consists of three imagers with different narrow (compared to all-sky view) field-of-view optics. One of the main scientific motivations relates to an earlier study by Knudsen et al. (2001) who used All-Sky Imager and TV camera observations to argue that there is a gap in the distribution of auroral arc widths around 1 km. With DAISY we will be able to show whether the gap is real or an instrumental artifact due to inadequate spatial resolution. If the gap is real, it would be an important clue in identifying the mechanisms of auroral arc generation. In this paper, we describe and discuss the DAISY imagers and show the width distribution of the auroral structures observed by DAISY prototype. We also compare our findings with the Knudsen et al. (2001) results.

1 Introduction

The majority of the existing auroral imagers are either all-sky cameras (e.g. Syrjäsuo et al., 2001; Donovan et al., 2003) with fish-eye optics or video rate TV cameras with very high spatial and temporal resolution (e.g. Trondsen, 1998). In the former case the spatial resolution of the instrument (although dependent on the size of the Charge Coupled Device (CCD)) typically allows good quality observations of 10–100 km sized auroral structures at the altitudes of 100–130 km with the temporal resolution of about 10–20 s. An advantage of the all-sky optics is the possibility to image a large area at once. All-sky cameras often use filter wheels to capture multiple single emission wavelengths. In case of the TV cameras the characteristic measurable scale size is usually about 100 m at a rate of 25 or 30 frames per second. Due to enormous amount of data, TV cameras have so far been operated on campaign basis only.

As pointed out by Knudsen et al. (2001), there are not enough observations of about 1 km sized auroral arcs to show that they exist. The lack of observations is either because these scale sizes do not exist or because the imagers in use cannot resolve that scale size well enough. Given that there are physical reasons why arcs of widths of about 1 km may be suppressed, this is an important issue to resolve (Lessard and Knudsen, 2001). Knudsen et al. (2001) studied a set of 3126 auroral arcs observed by a CANOPUS (Rostoker et al., 1995) all-sky camera in Gillam, Manitoba, Canada. They used images from the green auroral emission line (557.7 nm) to identify and analyse auroral arc widths. The arc widths were defined as full-width half-maximum values of the brightness profiles of the arcs mapped to the altitude of 135 km. The spatial resolution of the Gillam imager with the CCD of 200×200 pixels was 1.7 km at the zenith (at its best). Their results show that the typical auroral arc width is 18±9 km with a sharp cutoff at 3.4 km. These results were compared to earlier TV camera results by Maggs and Davis (1968) with the typical arc widths of some hundreds of metres. Knudsen et al. (2001) showed that there is a need for observations optimised for 1 km scale size to determine whether there is a real gap in the width distribution of auroral arcs. Two separate arc width distributions would imply two different mechanisms to form auroral structures of different sizes, which would be an important insight into the search for theoretical explanations for auroral arc formation. As an example of the arc formation mechanisms, recent theoretical work (Chaston et al., 2003) suggest that inertial Alfvén waves can drive auroral structures with widths of the order of 1 km near the polar cap boundary.

Auroral tomography has been developed from the satellite radio tomography (Austen et al., 1986). The idea of the method is to utilise data from several auroral imagers viewing the same auroral feature from different angles. From

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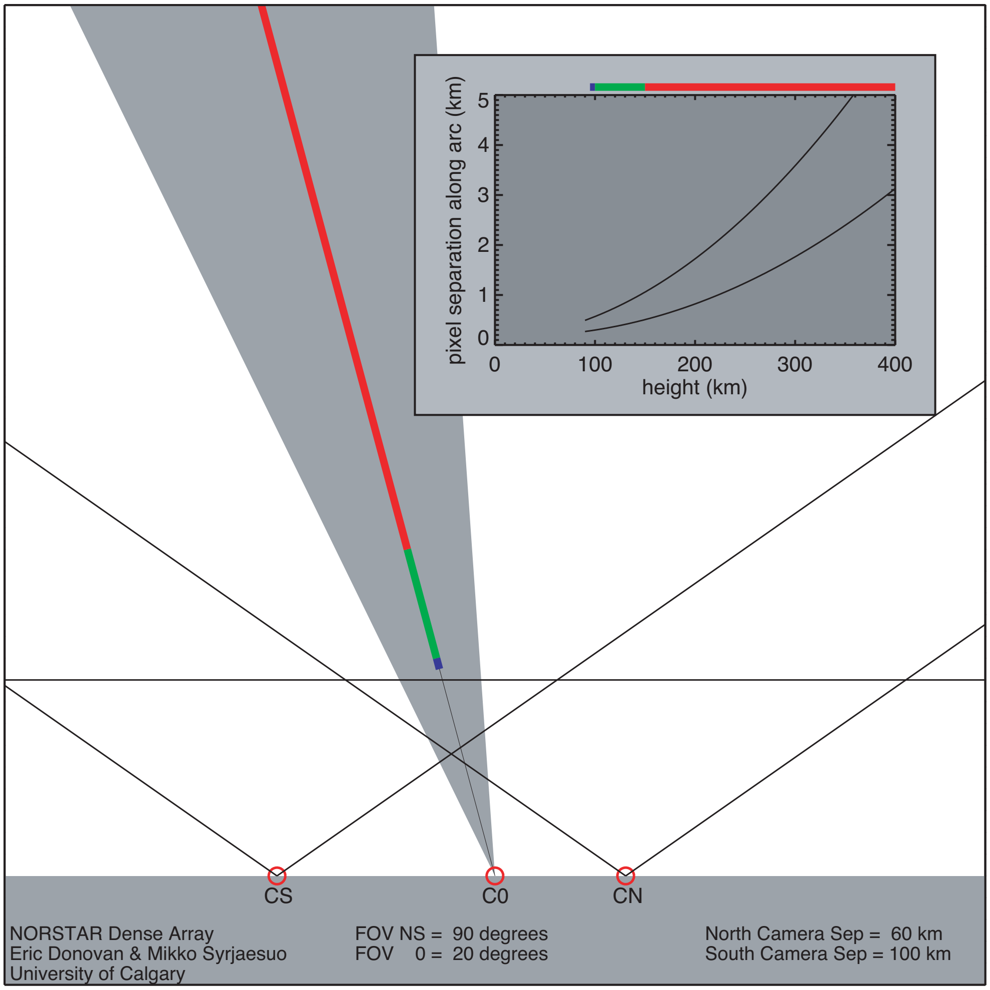

Fig. 1. A possible set-up for altitude profile studies with DAISY. This is a north–south cross-section where south is to the left and north is to the right. The imager in the middle (C0) has a FoV of 20° and looks directly into the aurora along the magnetic field line. The ones on either side, 60 km north of the middle one (CN) and 100 km south of the middle one (CS) have the FoVs of 90° and observe the same structure from the sides. The small panel in the right hand corner of the plot shows the altitude resolution of this set-up: up to the height of about 150 km the pixel separation is less than one kilometre, and up to about 300 km it is still less than 3 km.

these observations either a two-dimensional (latitude vs. altitude) or three-dimensional map of the volume emission rate can be inferred by using e.g. stochastic inversion (e.g. Nygrén et al., 1996) or iterative methods (e.g. Frey et al., 1998; Gustavsson, 1998). The horizontal resolution of the tomography results depends on the separation of the ground stations. According to Frey et al. (1996a,b), a reasonable distance between the imagers varies from 20 km to 200 km. The reliability of the result is also affected by the thickness and the width of an auroral arc, separation between the arc structures (multiple arcs) as well as the location and orientation of the aurora with respect to the imagers. Some a priori information needs to be included. In case of the stochastic inversion it is embedded in the regularisation, while in the iterative methods this information comes into play when choosing the start profile and the stop criteria for the iteration.

Tomography can be tackled with the three DAISY cameras. A planned set-up for this type of observation is shown in Figure 1, where the camera with the field-of-view (FoV) of 20° looks at the aurora directly from below and along the local magnetic field. The other two cameras with 90° FoVs observe the same auroral structure from either side. DAISY will allow high temporal and spatial resolution for this kind of experiment on campaign basis.

In this paper, we describe the imagers used in the Dense Array Imaging SYstem (DAISY). The DAISY cameras with narrow FoVs and high spatial resolution are designed so that the typical observable scale size is of the order of 1 km. This will allow us to ask and answer the question about the existence of the 1 km wide structures in the aurora. The first

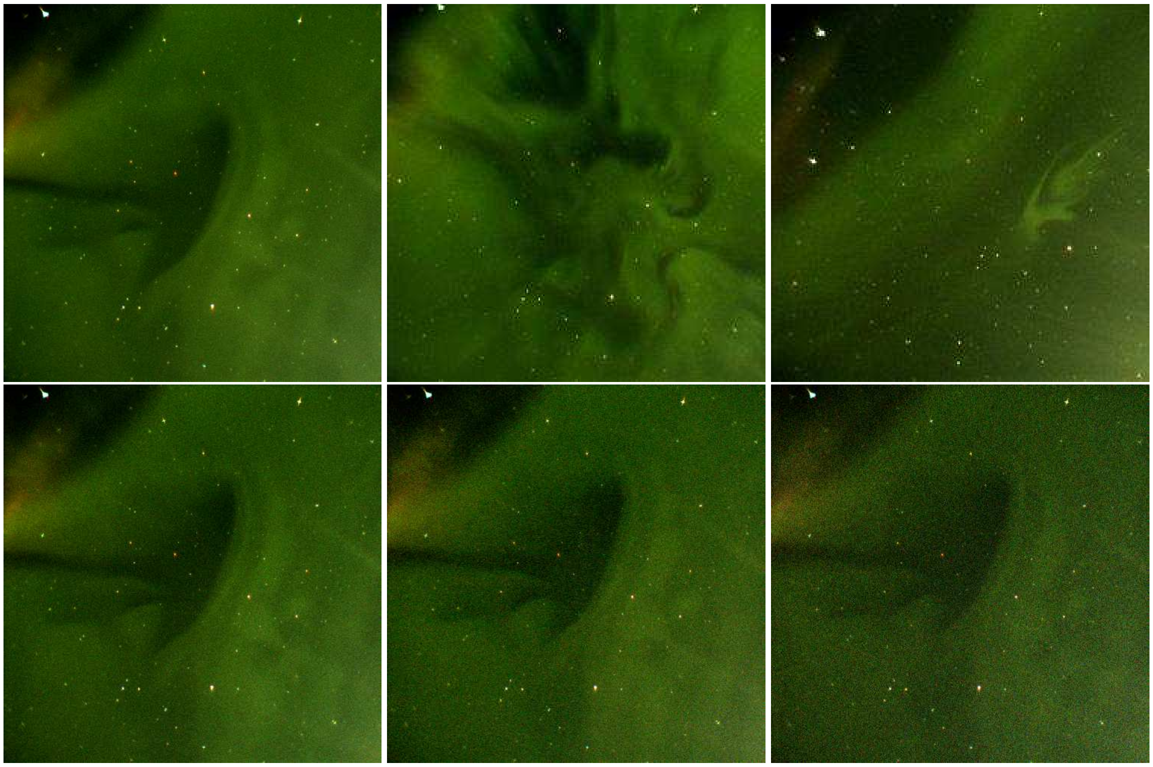

Fig. 2. Images taken by the DAISY prototype in Athabasca observatory with the FoV of 20°. The images in the top row were captured on 15 Feb, 2006 at 10:45 UT, 10:50 UT and 11:14 UT (from left to right) with the exposure time of eight seconds. The images in the bottom row are taken of the structure in the top left images (10:45 UT) but with exposure times of 4 s, 2 s and 1 s, respectively (left to right).

DAISY campaigns will take place during the winter 2006–2007. Here, we discuss the technical details of DAISY, and show some sample images and prototype data analysed in order to determine the arc widths.

2 DAISY cameras in more detail

DAISY consists of three imagers, one with the FoV of 20° and two with the FoVs of 90°. The prototype imager used optics with 60° FoV. All imagers incorporate a colour CCD (Starlight Xpress SXV-H9C) with 1392×1042 pixels and a 16-bit dynamic range. An infra-red filter with a bandpass of about 400–700 nm is placed in front of the CCD to block the contribution of the wavelengths longer than the visual ones. With 20° FoV and full pixel resolution the average spatial resolution at the altitude of 135 km is about 100 meters. A Bayer colour matrix is integrated into the CCD so that the image is read directly in RBG colour system (Sony data sheet). The data are stored in lossless raw format, which makes about two megabytes per image file. The system uses USB 2.0 and the time needed for reading one full image from the CCD is about three seconds. This together with about five-second exposures results in an imaging interval of about 10 seconds. A mechanical shutter is used to protect the CCD from direct sunlight during the day. It opens before the operation starts and closes at dawn, after the night's observations. A few examples of DAISY images are shown in Figure 2.

Because the colour matrix is integrated onto the CCD exact information on single emission line intensities cannot be deduced. However, if an intensity calibrated imager with narrow bandpass filters is operated at the same station, the broad-band red, green and blue channels from the colour CCD can be fit to correspond the auroral emissions at 630.0 nm (red), 557.7 nm (green) and 427.8 nm (blue) (Partamies et al., 2006).

The imagers are designed to be campaign instruments and operate in the field using an external power supply (e.g. a power generator). A photograph of the DAISY system is presented in Figure 3. The cameras are mounted in a small case together with a Global Positioning System (GPS), an Uninterruptible Power Supply (UPS), a temperature controller and a laptop computer to run the image capturing software. The camera mount allows the imagers to be manually aligned as best suited for the purpose of the campaign, e.g. to view along the local magnetic field. The camera box has a small dome on the top and a shipping cover that is used to protect the dome when transporting the instruments to the field. A wireless network connection can be used to monitor and

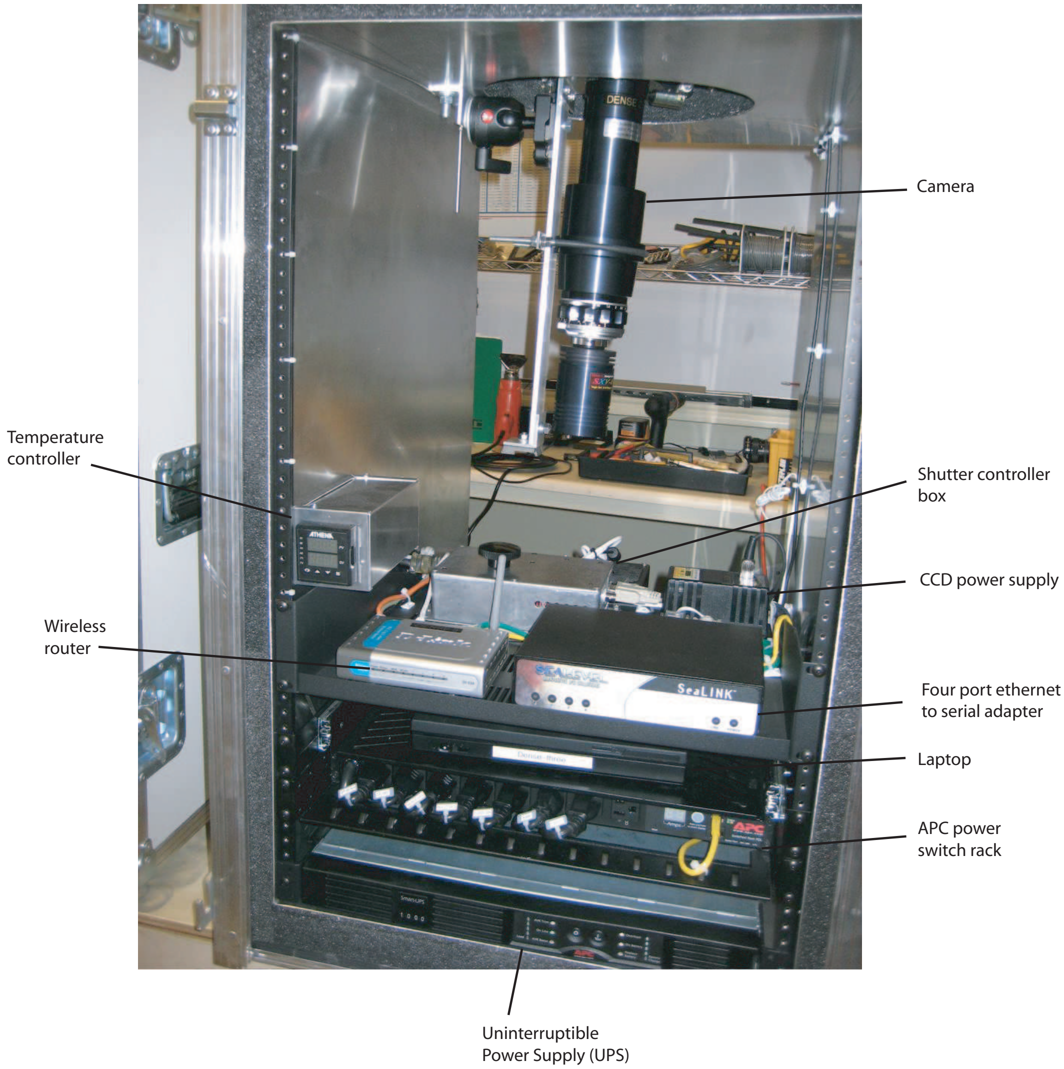

Fig. 3. A photo of the DAISY including the names of the parts inside the camera housing. In addition, there is a small dome and a GPS on the roof of the box.

control the imaging.

3 First DAISY prototype observations

The DAISY prototype was operated for the first time during a University of Calgary optical campaign in Churchill Northern Studies Centre in Manitoba, Canada, on 3–13 March in 2005. Churchill is located at the magnetic latitude of 68.57° (geographic latitude of 58.74°), which is directly under the statistical auroral oval giving almost 100% probability for auroral observations whenever the weather is clear at night. During this campaign, the DAISY prototype was standing outside without housing next to an all-sky colour camera, Rainbow (Syrjäsuo et al., 2005). Both imagers were covered by heating tape to keep from freezing (except during the first night). The available optics had a FoV of 60° resulting in an average spatial resolution of about 400 m at the altitude of 135 km. Good data with clear skies and aurora were captured during four nights. An example of simultaneous images from Rainbow and the DAISY prototype is shown in Figure 4.

We examined all the campaign data and found 31 narrow auroral structures in total. The auroral arc analysis presented here follows closely the one performed by Knudsen et al. (2001) to produce comparable results. The widths of the auroral structures were calculated from the relative brightness profiles. First, the minimum cross-section of the arc structure was determined by rotating a line along which the brightness profile was examined. After finding the smallest cross-section, a Gaussian function was fitted to the brightness profile to determine the full-width half-maximum (FWHM) value. Prior to the fit, the offset of the brightness curve was manually removed and thus, the fitting routine con-

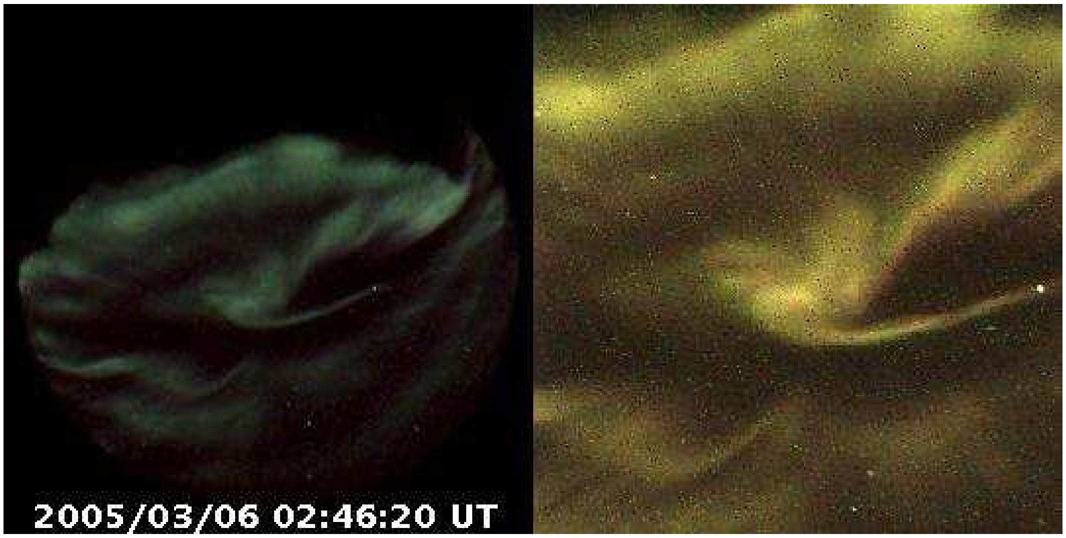

Fig. 4. Simultaneous images from the Rainbow all-sky camera (left) and the DAISY prototype with 60° FoV (right). The images were taken during the optical campaign in Churchill, Manitoba, on 6 March, 2005, at 02:46:20 UT. Some extra noise in these images is due to the fact that the instruments were operated outside in freezing temperatures without heating (during the first night). In the right hand half of the images, there is a thin auroral arc, whose brightness profile is analysed in Figure 5.

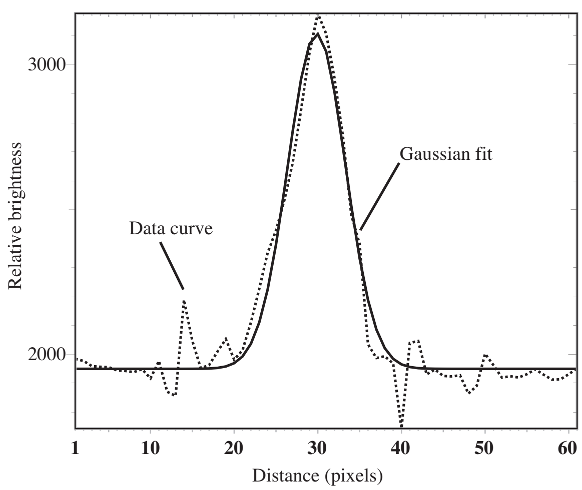

Fig. 5. An example of a Gaussian fit. The dotted curve is the relative brightness across the thin arc and the solid curve shows the Gaussian fit, which gives the FWHM value of the structure. The FWHM value for this fit is 3.5 km and the fit residual 6%.

tains only three free parameters: the amplitude of the Gaussian curve A_1, position of its maximum A_2 and the FWHM value A_3. The offset was set to be the minimum value of the curve slightly off the arc (background). This way we can keep as many data points as possible. The mathematical form of the Gaussian function can be written as $y = A_1 exp(-(x - A_2)^2/2A_3^2)$. An example of a brightness profile, together with a Gaussian fit, is shown in Figure 5.

The residual of the fit was defined as $R = \sqrt{\Sigma((y - \text{datapoints})^2)}/A_1$, where y is the fitted value and the datapoints give the corresponding values of the measured profile. Any events with the residual of 10% or more would have been excluded from the statistics but every brightness profile was in a very good agreement with the Gaussian function.

Knowing that one pixel corresponds to about 400 metres at the ionospheric altitudes the FWHM values were converted to widths in kilometres. This procedure was performed for each of the 31 narrow structures and resulted in a distribution shown in Figure 6 (solid line) together with the previous observations by Knudsen et al. (2001) (dotted line) and Maggs and Davis (1968) (dashed line).

The arc widths from the DAISY prototype range from 1.9 km to 14 km with the typical value of 4–6 km. Our measurements (solid line) of the thin auroral structures overlap with the small width end of the Knudsen et al. distribution (dotted line) with the thinnest structures being slightly thinner than the cutoff and the widest structures almost reaching the average arc width of Knudsen et al. (2001). The characteristic width found in this study (4–6 km) is close to the gap between the two previously reported width distributions but still in the tail of the Knudsen et al. distribution. Note also that the number of events in our data set is not yet comparable with the amount of arcs in the other two studies. In addition to the comparison of the scale sizes, we also note that the meso-scale auroral arcs recorded at Gillam (Knudsen et al., 2001) had a lifetime of at least three minutes. The arcs studied here using the DAISY prototype data lasted typically less than or of the order of one minute. Within a minute the thin structures usually drift or fade away, merge or split in a way

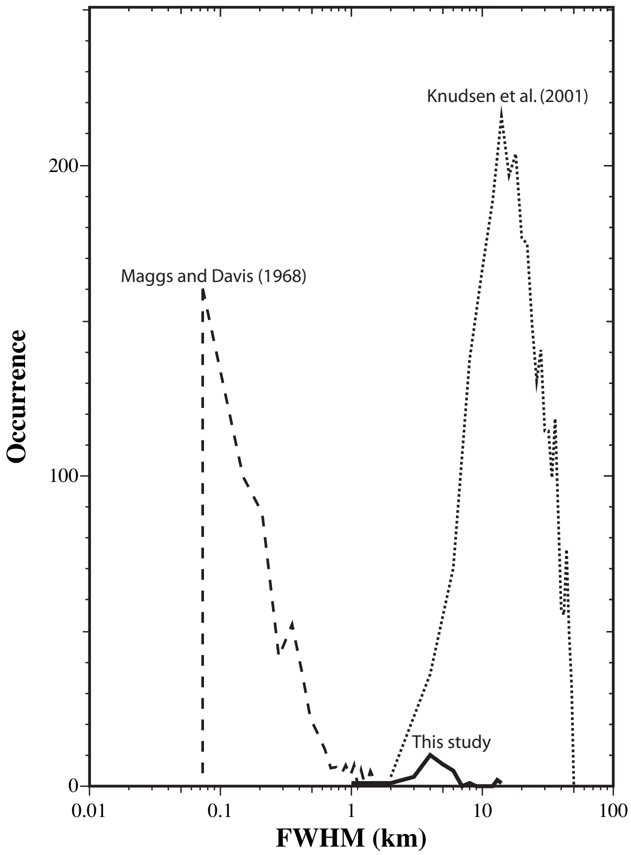

Fig. 6. Ditribution of the arc widths. Results from this study (solid curve), from Knudsen et al. (2001) (dotted curve), and from Maggs and Davis (1968) (dashed curve).

that the original well-defined thin structure disappears.

4 Summary and conclusions

We have described a new colour imager system, Dense Array Imaging SYstem (DAISY), that is designed to resolve auroral structures in 1 km scale size. A significant amount of observations in this range will answer the question about whether two different mechanisms work in producing two different scale sizes in the aurora, or whether the gap in between the observed scales by Knudsen et al. (2001) and Maggs and Davis (1968) is an instrumental artifact. The prototype data showed promising capabilities of the high spatial resolution and convincingly good fits to the Gaussian function. We measured 31 thin auroral structures from 1.9 km to 14 km wide (FWHM) with the mean value of 4–6 km.

DAISY is a campaign instrument and thus, capable of operating in the middle of the wilderness provided that an external power supply is available. It will be a great tool for auroral altitude profile and tomography type studies, although the data availability will be limited to campaigns. The first campaigns with DAISY will be run during the imaging season 2006–2007.

A future plan for a DAISY type imager is a continuous operation at a site together with an all-sky camera to provide the opportunity for continuous multi-scale auroral studies. A desirable campaign set-up for the future will, in addition to these two cameras, include a very high resolution TV rate camera to complete the scale size spectrum.

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