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Aurora

Estimating the peak auroral emission altitude from all-sky images

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ABSTRACT:

The Magnetometers Ionospheric Radars All-sky Cameras Large Experiment (MIRACLE) network monitors auroral activity in the Fennoscandian sector of Europe. Some of the MIRACLE network stations include digital all-sky cameras (ASC, FoV 180°) that have been in operation since 1996. ASCs are geared towards morphologic studies of meso-scale (10-1000 km) aurora. The FoVs of the cameras overlap allowing optical triangulation and tomographic-like reconstruction of auroral features. The goal of this study is to evaluate the value of optical triangulation to estimate the altitude at which the peak auroral emission occurs using ASC images. The technique was tested for a thin stable auroral arc on November 22, 2000. The auroral arc was observed by ASCs located at the Abisko, Kilpisjärvi, Kevo and Muonio stations from 17:32:00 until 17:38:00 UT. The analysis presented in this paper deals only with the first pair of stations. The Auroral Image Data Analysis (AIDA) tools (a Matlab software package) was adapated for ASC geometry and used to triangulate the altitude of the auroral arc. Results showed that the peak emission altitude varied along the structure by about 40 km. Since the uncertainty for each measurement was at most 20 km, this variation along the auroral arc is physically significant. The average altitude (120-140 km) of the auroral stucture is in agreement with the altitude determined with the image matching method but it is greater than the most frequent altitude observed in prior studies (110 km).

Keywords: Aurora, Optical Triangulation, All-Sky Cameras.

REFERENCIAS Y ENLACES / REFERENCES AND LINKS

[1]. C. Størmer, "Altitudes of aurorae", *Nature* **97**, 2418 (1916).

[2]. J. H. Brandy, J. E. Hill, "Rapid determination of auroral heights", *Can. J. Phys.* **42**, 1813-1819 (1964).

[3]. J. E. Hill, "Auroral heights over Churchill, Manitoba, during International Quiet Solar Year", *Can. J. Phys.* **43**, 1917-1919 (1965).

[4]. J. Boyd, A. Belon,d G. Romick, "Latitude and time variations in precipitating electron energy ingerred from measurments of auroral heights", *J. Geophys. Res.* **76**, 7694-7700 (1971).

[5]. N. Brown, T. Davis, T. Hallinan, H. Stenback-Nielsen, "Altitude of pulsating aurora determined by a new instrumental technique", *Geophys. Res. Lett.* **3**, 403-404 (1976).

[6]. K. Kaila, "An iterative method for calculating the altitudes and positions of auroras along the arc", *Planet. Space Sci.* **35**, 245-248 (1987).

[7]. M. Syrjäsuo, T. I. Pulkkinen, P. Janhunen, A. Viljanen, R. J. Pellinen, K. Kauristie, H. J. Opgenoorth, S. Wallman, P. Eglitis, P. Karlsson, O. Amm, E. Nielsen, C. Thomas. "Observations of substorm electrodynamics using the miracle network", in Substorms-4, volume 238 of Astrophysics and Space Science Library, page 111 (1998).

[8]. B. Gustavsson, *Three Dimensional Imaging of Aurora and Airglow*, PhD Thesis, Swedish Institute for Space Physics (2002).

[9]. U. Brändström, *The Auroral Large Imaging System - Design*, Operation and Scientific Results, IRF Scientific Report 279, Kiruna, (2003).

[11]. K. Kaila, "Determination of the energy of auroral electrons by the measurements of the emission ratio and altitude of aurorae", *Planet. Space Sci.* **37**, 341-349 (1989).

1. Introduction

The photographic method for finding the height and position of auroral structures was first implemented by Carl Størmer [1] in 1916. He used a pair of state-of-the-art photographing devices separated by 4 to 28 km to evaluate the height of the lower border of auroral forms by graphically fitting the whole auroral form to the same altitude (i.e. locating corresponding points on pairs of images). Størmer succesfully determined thousands of auroral heights and obtained an average value of 105 km. Some auroral forms differed from this value by tens of kilometers but most lay within the 100 – 110 km range. The advent of all-sky cameras (ASC), by photographing the whole sky in each image allowed for more extensive and systematic use of photographic triangulation. Brandy and Hill [2] used a rapid graphic method to evaluated the height of aurorae from images captured by two ASCs with field-of-view (FoV) of 150º. Hill [3] studied about 1200 images and obtained auroral altitudes ranging from 63 to 240 km and a most frequent altitude of 110 km. Boyd *et al.* [4] estimated auroral heights at different latitudes and local times and Brown et al. [5] evaluated the altitudes of pulsating aurorae using narrow angle sensitive TV-cameras and found an average altitude of 92±3 km. All of these studies relied on "image matching", meaning the necessity to find corresponding structures in two images. Kaila [6] developed a 3-D iterative optical triangulation method where matching points are not needed. Mathematically, triangulation is the process by which the position of a point is determined by measuring angles to it from two known locations. Kaila [6] adapted this technique to ASC pair by minimizing iteratively the distance between line of sights from each ASC to the auroral form and obtained average heights of 112±3 km and 94±4 km for the two thin auroral arcs present in the images recorded on high sensitivity color film. With this method it was also possible to see variations in auroral altitude with longitude ranging from 5 to 20 kms.

In this article we present triangulation and image matching results using ASCs (FoV 180o) from the Magnetometers Ionospheric Radars All-sky Cameras Large Experiment (MIRACLE, [7]) network. These digital ASCs have been in operation since 1996 and are imaging from September until April (start and end time of operation vary with station position). As shown in Fig. 1., the stations located in Lapland, northern Finland, over a range of latitudes from 65º to 70º north. The FoVs of the MIRACLE ASCs overlap enough for triangulation purposes.

The digital ASCs used for this study consist of an optical system, an image intensifier and a charge-coupled device (CCD, see Fig. 2.). They are referred to as intensified CCD cameras (ICCD). The fish-eye lens provides a circular field of view area with a diameter of approximately 600 km at 100 km altitude. The filter wheel consists of seven different slots. Three slots hold

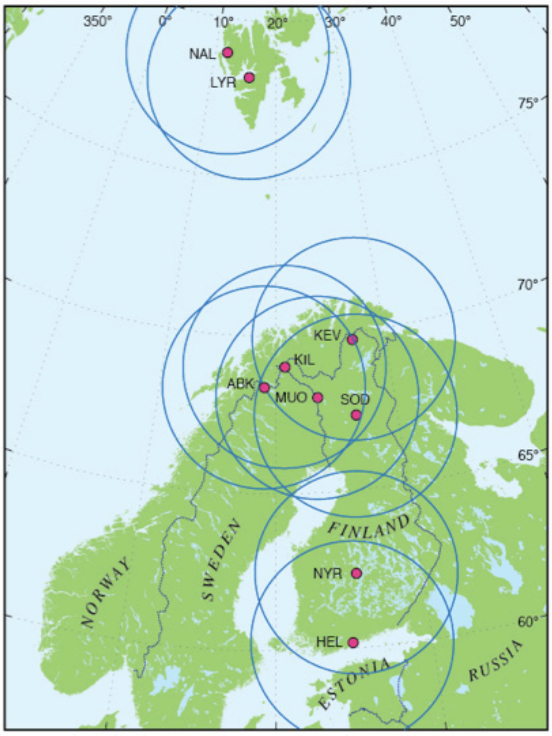

Fig. 1: Location of the ASCs from the MIRACLE network. The small red circles represent the location of the station and the big blue circles represent the field-of-view of each camera at an altitude of about 100 km.

narrow bandwidth (2.0 nm) interference filters for wavelengths 557.7 nm (green line), 427.8 nm (blue line) and 630.0 nm (red line). These are the main three wavelengths of the auroral emission and originate from excited states of atomic oxygen (green and red lines) and molecular nitrogen ions (blue line) in the upper atmosphere. One of the remaining slots is keptempty to record panchromatic (also called white light) images. The stars visible in panchromatic images are used for the geometric calibration of the optical system. This calibration determines the optical parameters (e.g. focal length) and the orientation (e.g. zenith position, direction of true north) of the camera and is essential for triangulation purposes.

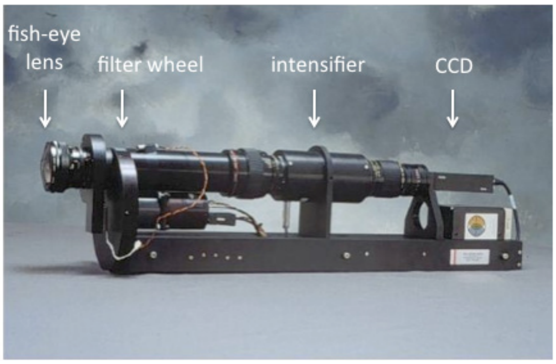

Fig. 2: Main components of an intensified CCD (ICCD) camera, manufactured by Keo Consultant.

2. Event selection and analysis

This study is the preamble to a more extensive statistical study aimed at evaluating the altitude at which the peak auroral emission is produced over a long time period and wide ranging set of conditions (e.g. variations with local time, latitude, geomagnetic activity). To investigate the performance of the triangulation algorithm with ASC images, it was necessary to find a first event with a “simple” auroral feature within the FoV of as many MIRACLE ASCs as possible (i.e. clear skies above each station location). The “simplest” auroral form is a thin auroral arc. One event, on November 22, 2000 satisfied these criteria. A thin single arc appeared slightly before 17:32 UT and disapeared after 17:38 UT and was visible by cameras in Muonio (MUO), Abisko (ABK), Kilpisjärvi (KIL) and Kevo (KEV). Only the best case, the ABK-KIL station pair, is presented in this article. Images captured at 17:34:00 UT from both stations are shown in Fig. 3. The images are filtered for the 557.7 nm. Geomagnetic conditions for that night in the Fenno-scandian sector are considered quiet.

Triangulation of the aurora was performed using the Auroral Image Data Analysis (AIDA, [8]) tools adapated for ASC geometry. AIDA is a Matlab-based software package originally developed for the Auroral Large Imaging System (ALIS, [9]) located in northern Sweden. The altitude values obtained along the thin auroral arc are shown in Fig. 4 for seven time steps. The mean altitude and standard deviation calculated for each time step are indicated in pink. It can be observed that the altitude of emission varies along the arc and decreases from west to east. This trend is linked to changes in emission spatially and temporally. Figure 5 shows the difference in emission between two consecutive images. For example, the image labeled 17:33:33 UT displays the difference in intensity between the images recorded at 17:33:00 and 17:34:00 UT. In images filtered at 557.7 nm light emission intensifies between 17:34:00 and 17:35:00 UT (image at 17:34:30 UT in Fig. 5) in the eastern part of the auroral arc, but during the same time period in images filtered at 630.0 nm light emission intensifies in the western side of the images. Auroral emission is caused by high-energy (1-20 keV) particles precipitating down on the upper atmosphere where they ionize and excite the atoms and molecules present. In turn, ionization produces secondary electrons (~1 keV) that will also excite the ions. When ions return to a stable state they will emit light. The altitude of auroral emission depends on the energy of the primary electrons. High-energy electrons penetrate deeper into the atmosphere and deposit their energy at lower altitude (i.e resulting mainly in green light at 557.7 nm and blue light at 428.7 nm) and low-energy electrons deposit their energy at higher altitude (i.e. resulting mainly in red emission at 630.0 nm) [11].

The average altitude estimates obtained with triangulation were compared with results from image matching. Image matching was carried out using the data display program Ihmetys. An

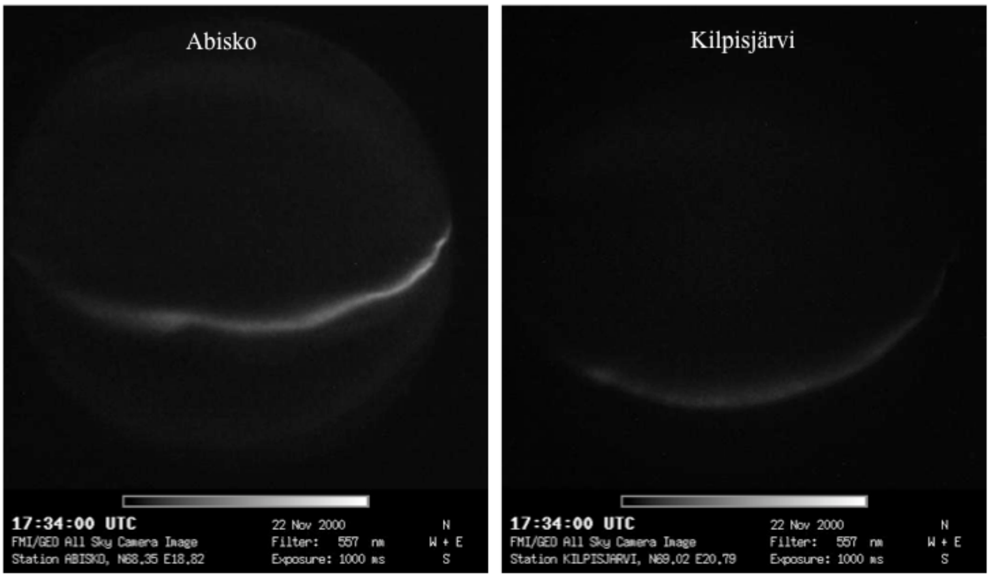

Fig. 3: Images from the Abisko and Kilpisjärvi cameras on November 22, 2000 at 17:34:00 UT. The images are filtered for the 557.7 nm wavelength and displayed in greyscale. The exposure time is 1 s.

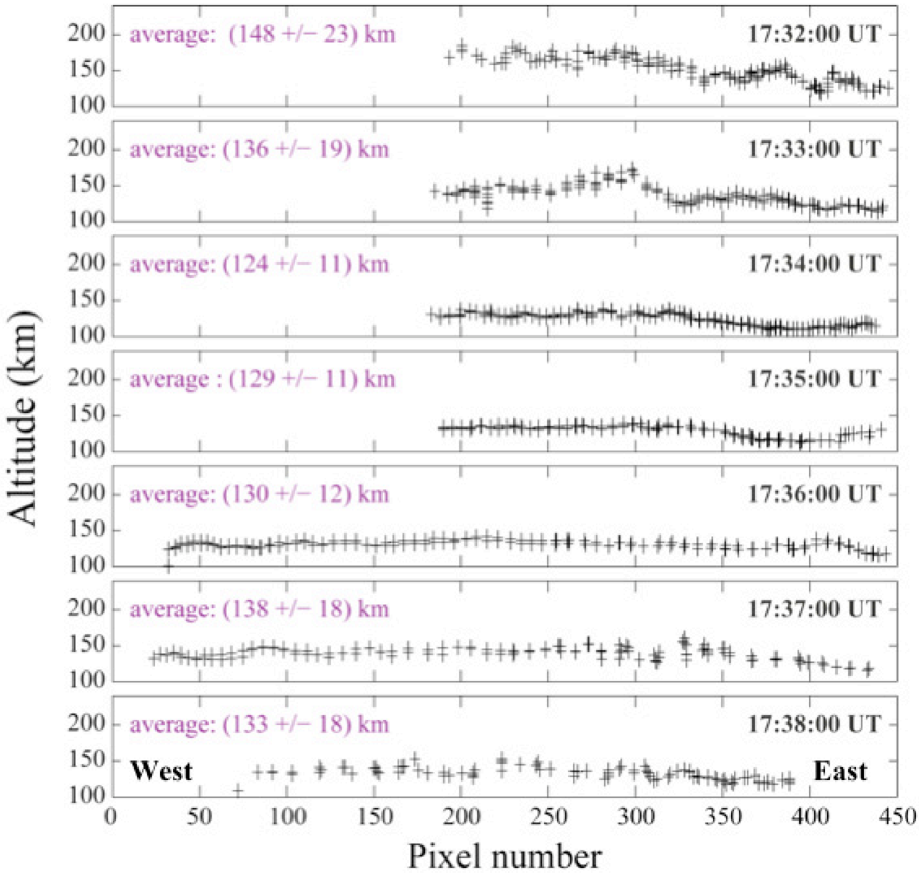

Fig. 4: Altitude triangulation along the auroral arc shown in Fig. 3., plotted from west to east. Images are recorded from 17:32:00 UT until 17:38:00 UT every minute and are filtered for the 577.0 nm wavelength. The average altitude and standard deviation are indicated in pink for each image.

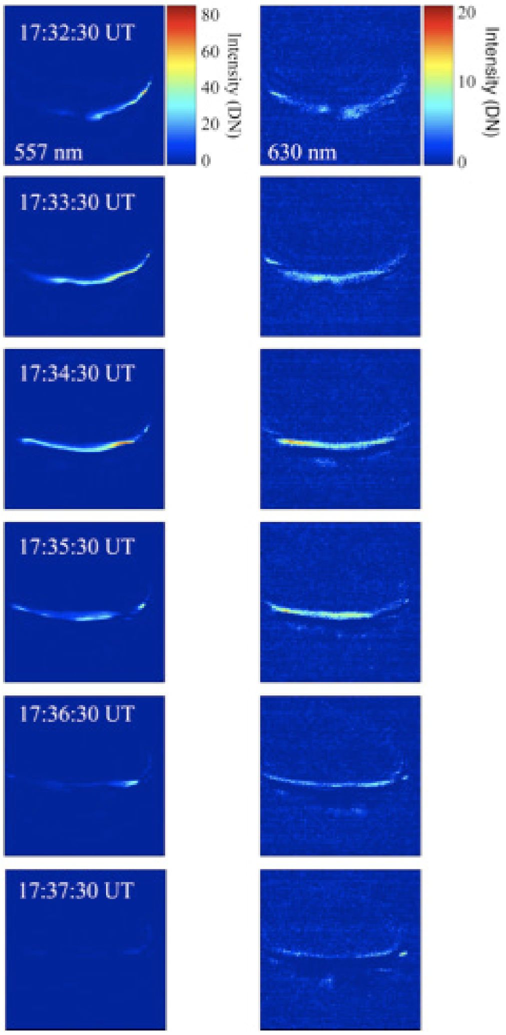

Fig. 5. Difference in intensity (data numbers) between two consecutive images from the Abisko camera. Left-hand side column is for images filtered at 557.7 nm wavelength and right-hand side column for simultaneous images filtered at 630.0 nm wavelength. For example, the image at 17:34:30 UT corresponds to difference in intensity between the images recorded at 17:34:00 and 17:35:00 UT. North is towards the top and west towards the left of each image.

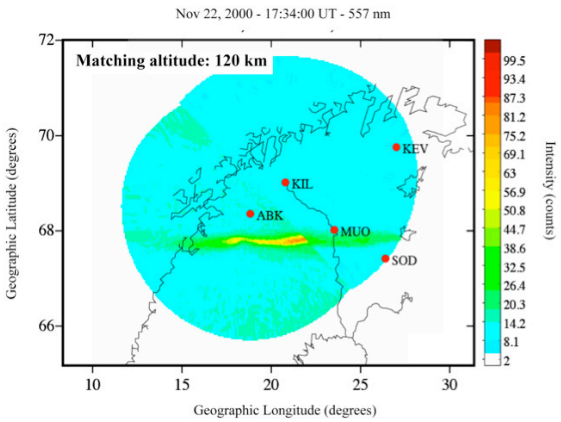

Fig. 6. Images from the Abisko and Kilpirjärvi projected at an altitude of 120 km used for image matching.

example is shown in Fig. 6. where the ASC images from the ABK and KIL stations are plotted on the map assuming the emission occurs at 120 km. The best matching altitude is that for which the thin auroral arc is the most continuous from one FoV to the other. The average auroral altitudes obtained by triangulation and image matching are presented in Table I. The decrease in auroral altitude around 17:34-17:35 UT is present for both methods and is likely due to an increase in average precipitating energy. Although it is easy to see the difference in precipitating energy along the east-west direction, it is impossible to estimate the average energy values without intensity calibrated images.

TABLE I

Average auroral altitude obtained with image matching and triangulation

Time (UT)	Best matching altitude (km)	Triangulated average altitude (km)
17:32:00	140±10	148±23
17:33:00	130±10	136±19
17:34:00	120±10	124±11
17:35:00	120±10	129±11
17:36:00	120±10	130±12
17:37:00	130±10	138±18
17:38:00	140±10	133±18

3. Discussion and conclusions

The preliminary results show that triangulation and image matching using ASC images are relevant techniques. Moreover, triangulation of thin auroral arc showed that the peak emission altitude varied along the structure by about 40 km. Since the uncertainty for each measurement was less than 20 km in most cases, this result is physically significant. Altitude variations of over 20 km were also observed over time. These changes in altitude, spatially and temporally, are linked to changes in the energy of the precipitating particles causing the auroral structure. The average altitude of the thin auroral arc determined in this study is greater than previous studies, underlining the need for rigorous extensive characterization of the altitude at which aurora occurs.

Acknowledgements

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