

**REPORT DOCUMENTATION PAGE**

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 20-October-2000	3. REPORT TYPE AND DATES COVERED Final Report	
4. TITLE AND SUBTITLE Combined Svalbard EISCAT Radar and Optical Observations for Polar Cusp/Cap Research			5. FUNDING NUMBERS F61775-99-WE025	
6. AUTHOR(S) Professor Alv Egeland				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Oslo PO Box 1048 Blindern Oslo N-0316 Norway			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 802 BOX 14 FPO 09499-0200			10. SPONSORING/MONITORING AGENCY REPORT NUMBER SPC 99-4025	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (Maximum 200 words)  This report results from a contract tasking University of Oslo as follows: The contractor will merge the capabilities of the Svalbard EISCAT Incoherent Scatter Radar and the polar network of optical imagers and radio beacon receivers to define the polar and noon auroral processes that are directly and indirectly driven by the interplanetary magnetic field. The goal of this research is to assess the ability to move from observation of present conditions to a degree of prediction of future conditions.				
14. SUBJECT TERMS EOARD, Space Science, radar, Ionosphere, Atmospheric Emission			15. NUMBER OF PAGES 13	
			16. PRICE CODE N/A	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18  
298-102

# ***FINAL REPORT***

*on*

***Grant No F61775-99-WE025***

***“COMBINED SVALBARD EISCAT RADAR AND OPTICAL  
OBSERVATIONS FOR CUSP/POLAR CAP RESEARCH”***

*by*

Professor Alv Egeland, PI  
Professor Jøran Moen, Co-PI

10 October, 2000

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**Correspondence to:**  
Prof. Alv Egeland  
Department of Physics  
P.O. Box 1048, Blindern  
N-0316 Oslo, Norway  
e-mail: [alv.egeland@fys.uio.no](mailto:alv.egeland@fys.uio.no)  
Fax: +47 22 855671  
Phone: +47 2285 5672

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AQ FOI-11-2344

**Project title:** *Combined Svalbard EISCAT Radar and Optical Observations for Cusp/Polar Cap Research*  
**Grant No:** F1775-99-WE025

## **BACKGROUND INFORMATION**

Svalbard is a unique place in the Northern Hemisphere for studies of dayside cusp and polar cap auroras as well as related phenomena within the cusp-, cleft-, low-latitude boundary layer- and mantle-regions.

The EISCAT Svalbard Radar (ESR) at Longyearbyen has been in operation during this contract period. The ESR is a third generation incoherent scatter radar of highest standard. Its 32-m diameter antenna is movable over  $360^{\circ}$  in azimuth and from  $0$  to  $180^{\circ}$  in elevation. This radar is located on the Gruve 7 – mountain, within 6 km from Longyearbyen Auroral Station. A new radar antenna, allowing simultaneous observations in two different directions was officially opened in May this year. With ESR now in full operation we will vastly enhance our rate of progress in the key areas of the scientific field of this Grant, in the years to come.

The Ny-Ålesund (geographic lat.  $78.9^{\circ}\text{N}$ ; geomagnetic lat.  $76.1^{\circ}\text{N}$ ) and Longyearbyen Auroral observatories (geographic lat.  $78.2^{\circ}\text{N}$ ; geomagnetic lat.  $75.3^{\circ}\text{N}$ ) are the master stations in our Svalbard network. Meridian scanning photometers (MSP) and all-sky CCD imagers at different wavelengths comprises the core of optical instrumentation.

Svalbard is nearly 12 hours separated in magnetic time from the Alaska sector and its conjugacy to stations in Antarctica makes Svalbard even more attractive. The Svalbard climate - due to the Gulf Stream - is unusual mild. Thus, there is no other place at the same geographic latitudes as our stations on Svalbard in which the comforts of modern living can be enjoyed, and is so accessible from the world's largest metropolises. In addition, we have a long tradition for auroral and polar ionospheric research in Norway.

The new, two dimensional mapping of the polar ionosphere above Svalbard studying coherent scattered signals from the HF radars (SuperDARN) also constitute a powerful tool for investigations of both temporal and spatial behaviour of the polar electrodynamic, as demonstrated in this report.

Whenever possible, our ground observations have also been correlated with in-situ measurements from low-altitude polar orbiting satellites as well as space platform observations of the solar wind.

## **OBSERVATIONS CARRIED OUT AND CAMPAIGNS PLANNED**

Optical measurements by meridian scanning photometers and all-sky CCD imagers at different wavelengths have been carried out continuously (when weather permitted) in the period from 20 November to 20 January. In addition, the five ground magnetic stations covering 10 degrees in latitude from Tromsø to Ny-Ålesund have been in continuous operation.

During the auroral season the EISCAT Svalbard radar has been operated as often as possible and coordinated experiments carried out. In addition, data from the SuperDARN HF radars – with large fields of view over-looking the Svalbard area, have been used in several studies (cf. next section)

During this year we have also met twice with researchers from the research team at AFRL, Hanscom AFB. A large experimental campaign has been planned for January next year. The period 14-28 January has been selected. We have been in close contact with the people responsible for the EISCAT Svalbard Radar and asking for minimum 40 hours experiment time during this period. In addition to the instruments mentioned above, scintillation measurements will be carried out at Ny-Ålesund, and a new high performance all-sky CCD camera will be tested out. We have also invited the SuperDARN team at the Leicester University, UK, to participate in this campaign.

From 25 November to approximately 10 December this year, an auroral rocket campaign will be carried out at Svalbard during which continuous ground observations will be made.

## **SCIENTIFIC RESULTS**

Knowledge of the polar ionosphere provides direct information of the space plasma, the main constituent of our Universe. Even though we have visited most regions of our ionosphere, magnetosphere and all the way out to the Sun, we still only know bits and pieces. The role of the polar ionosphere and its boundaries are substantial for further space weather predictions.

The only way to continuously monitor the energy transfer from the solar wind via the dayside magnetopause to the polar ionosphere is through the ground-based remote observations of their ionospheric footprints. The ionospheric cusp/cleft dynamics above Svalbard have been investigated by multi-instrument techniques including radars, optics and ionospheric tomography during several campaigns. Below is given a brief report on the major results divided in three main themes:

- 1) Interplanetary Magnetic Field (IMF) regulated cusp auroral dynamics.
- 2) Structuring of ionospheric plasma in the cusp.
- 3) Monitoring of the polar cap boundary by radars.

### ***IMF regulated cusp auroral dynamics:***

The complex chain of mechanisms involved in the transfer of solar wind energy, momentum and particles into the magnetosphere-ionosphere system manifests itself in the aurora as a rich spectrum of activities. Systematic work on cusp/cleft auroral morphology, however, has enabled us to classify dayside auroral activities as function of IMF clock angle (Moen et al., 2000a). Cusp auroral activities near noon are subdivided in three main configurations, which corresponds to three different regimes of IMF clock angles in the Z-Y plane:

- The type 1 aurora occurs typically in the latitude range from  $70^{\circ}$ - $74^{\circ}$  MLAT under southward IMF conditions, i.e. for clock angles between  $90^{\circ}$ - $180^{\circ}$ .
- Another auroral form (type 2) is typically located between latitudes  $\sim 78^{\circ}$ - $79^{\circ}$  MLAT for strongly northward IMF conditions (clock angles between  $0^{\circ}$ - $45^{\circ}$ ).
- Thirdly, for clock angles between  $45^{\circ}$  and  $90^{\circ}$ , an intermediate state of co-existing type 1 and 2 forms are common.

Type 1 aurora is interpreted as a signature of low-latitude boundary layer reconnection. Type 2 is related to lobe reconnection, and the intermediate state may be indicative of reconnection at both places simultaneously. The type 1 auroral activity includes the classical poleward moving auroral forms (PMAFs) near magnetic noon of which location and motion pattern are strongly regulated by the IMF orientation (Sandholt and Farrugia, 1999). Since it was first suggested by Sandholt in the mid-eighties, it has been an ongoing debate on whether or not this event class actually is a footprint of pulsed magnetopause reconnection.

Moen et al. (1999) monitored the IMF  $B_Y$  control of the motion pattern and the location of the cusp auroral activity in response to an IMF  $B_Y$  polarity change from -15 nT to +15 nT in the course of 20 minutes. Figure 1 displays a sequence of red line filtered all-sky camera images covering the time interval from 0948.54 UT to 1019.40 UT on December 24, 1995. From 0948.54 UT onwards we see an auroral expansion eastward across the field of view from a location south-west of Svalbard. The fading phase of this event is illustrated by the 0954.55 UT image. Immediately after this eastward moving form faded, a new form started to brighten south-east of Svalbard at 0957.55 UT, at a location adjacent to, but east of where the former faded. The initial brightening from this new location faded at 0959.25 UT, and was followed by a sequence of westward moving forms. The third event in the sequence expanded westward across the whole camera field of view (1015.10-1019.40 UT). This was the first time ever that a direct observation of an IMF  $B_Y$  regulated shift in the longitudinal position of the auroral cusp has been documented. The IMF  $B_Y$  regulation of the cusp is regarded to be a unique signature of magnetopause reconnection. The zonal shift of the cusp centre was estimated to be at least 3 hours in magnetic local time for that particular case. The observations indicated that the cusp reconfigured within a few minutes after the  $B_Y$  polarity change imposed on the magnetopause.

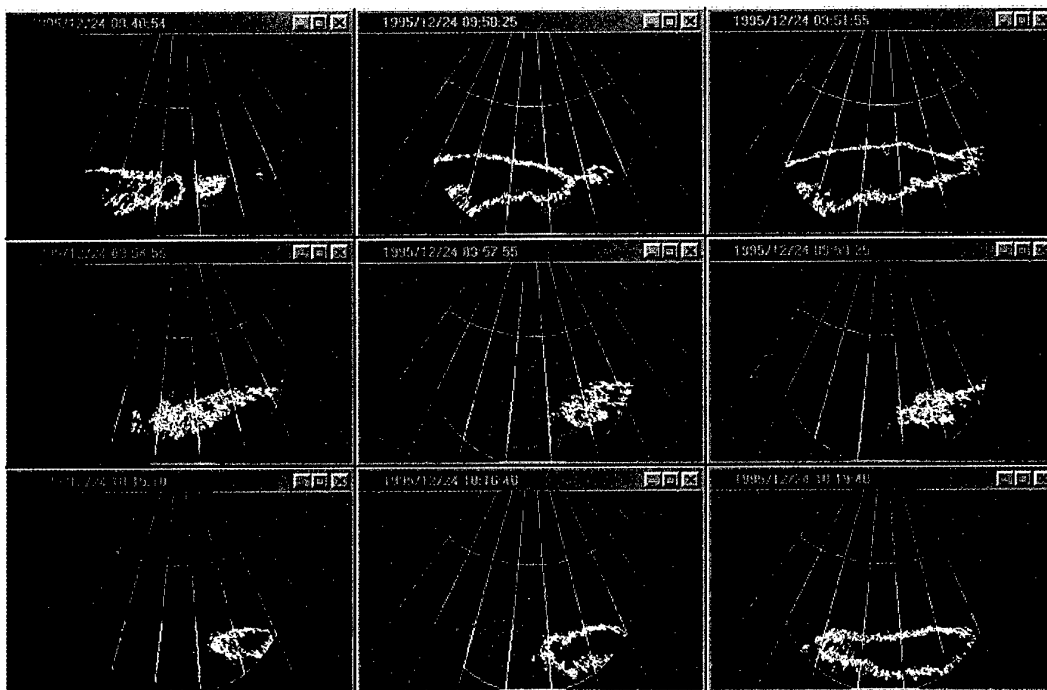


Figure 1. A sequence of digital all-sky images of the 630.0 nm emission taken at Longyearbyen displayed on a geographical frame of reference. The auroral emission is mapped to an Earth-centred sphere at 250 km. Time is given at the top of each frame.

Recently, we have identified another important dynamic feature of cusp aurora, described by Sandholt et al. (2000). This characteristic feature consisting of a two-phase activation of latitudinally separated type 1 and type 2 auroral forms. In each case an initial brightening at the cusp equatorward boundary (type 1 aurora) is followed typically within 2-3 min by a second brightening (type 2 aurora) separated to the north. This type of auroral bifurcation events often appears in a sequence of events recurring typically every 5-10 min. The phenomenon is observed when the interplanetary magnetic field (IMF) has a substantial east-west component,  $B_Y$ , (IMF clock angle range  $45^\circ$ - $140^\circ$ ). Local ground magnetic deflections corresponding to the activations of merging and lobe convection cells accompany the two-phase auroral brightenings. Thus, the two branches of the auroral bifurcation may correspond to magnetopause reconnection events, taking place respectively equatorward and poleward of the cusp. A review of data from the past ~20 mid-winter optical observation campaigns in Svalbard reveals that this phenomenon is occurring practically every day.

The combination of EISCAT Svalbard Radar (ESR) and optics has provided new opportunities to study detailed dynamics of the ionospheric cusp. Moen et al. (2000b) conducted a convection mode experiment with the ESR pointing towards magnetic north at a fixed  $45^\circ$  elevation within the scan-plane of the photometer. Figure 2 displays

electron density and ion velocity acquired by ESR from 0705 – 0755 UT on January 23, 1998. The raw data have been processed with a post-integration time of 1 min (highest resolution achievable on this particular day) and plotted versus time and altitude. Two intervals of strong poleward flows (0705-0712 UT and 0738-0755 UT) were interspaced by an interval of multiple arcs (0712-0738 UT). The intervals of strong poleward flows coincide with sequences of PMAFs. PMAF's moving across the radar field of view appear as tilted features (increasing altitude with increasing time) of enhanced electron density, annotated P1 to P4 on the top of Figure 2.

Interesting plasma dynamical features were revealed by this simplest possible convection mode of the ESR, such as IMF  $B_Y$  regulated shifts of the cusp inflow region and cusp related ionization blobs pushing through the ambient incompressible plasma. Multiple morning discrete arcs were found to be aligned with convection streamlines equator-ward of the flow reversal, whilst plasma in the polar cap inflow region streamed perpendicularly across the optical cusp boundary, as earlier anticipated. Notably, the reconnection rate associated with a sequence of cusp auroral transients was strongly time varying, but was not pulsed with the recurrence frequency of the optical events.

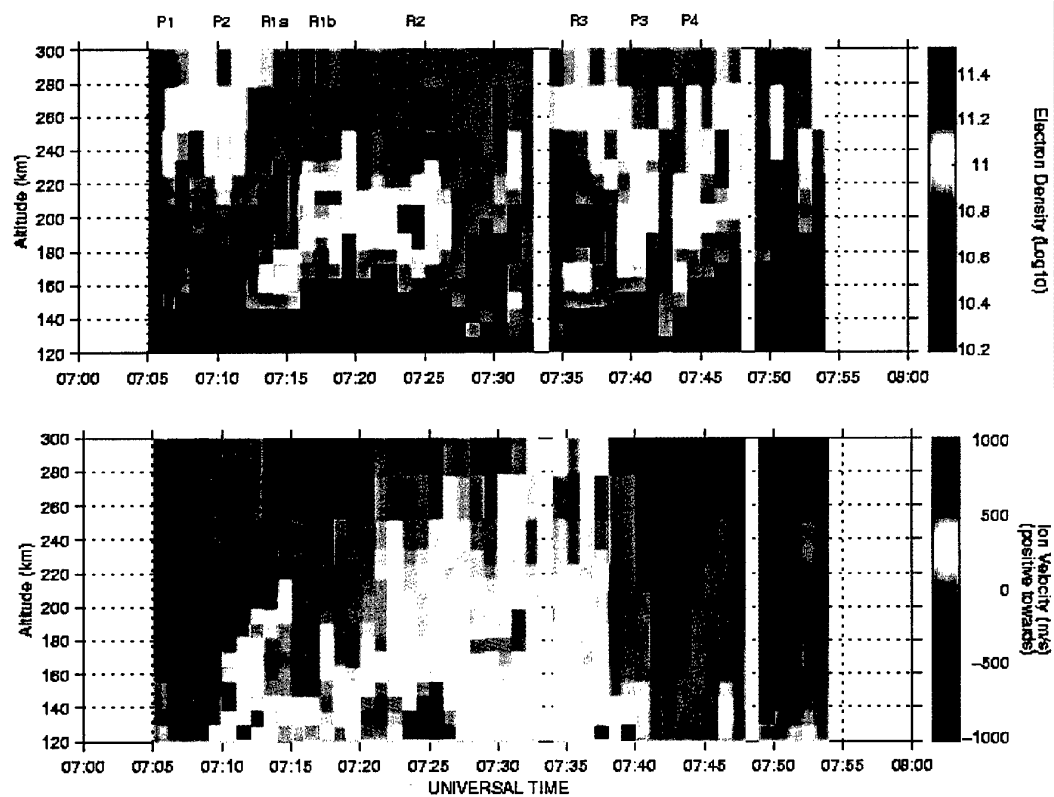


Figure 2. Electron density and ion velocity measured by ESR. The ESR was fixed in the magnetic meridian plane pointing north at 45 degrees elevation. The raw data have been processed with GUISDAP using 1 min post-integration.

**Structuring of ionospheric plasma in the cusp:**

The spatial structuring of ionosphere plasma in association with type 1 and type 2 auroral activities has been studied by radio tomography (Phryse et al., 1999; 2000; Walker et al., 1999). The radio tomography monitoring system comprises receivers at Ny-Ålesund (78.9°N, 12.0°E), Longyearbyen (78.2°N, 15.3°E), Bjørnøya (74.5°N, 19.0°E) and Tromsø (69.8°N, 19.0°E). Measurements are made of total electron content using signals from satellites in the Navy Ionospheric Monitoring System (NIMS). In Phryse et al. (1999) we studied a case of enhanced type 2 aurora observed by a meridian scanning photometer. Reversed ion energy dispersion measured during a DMSP satellite pass provided evidence for lobe reconnection. Tomographic imaging of the spatial plasma distribution revealed key footprints of the processes, including the location of the adiaroic boundary separating the lobe cells from the closed LLBL-precipitation, the dispersion of precipitating soft ions along sunward convecting field lines, and the possible presence of Birkeland current sheet at the adiaroic boundary.

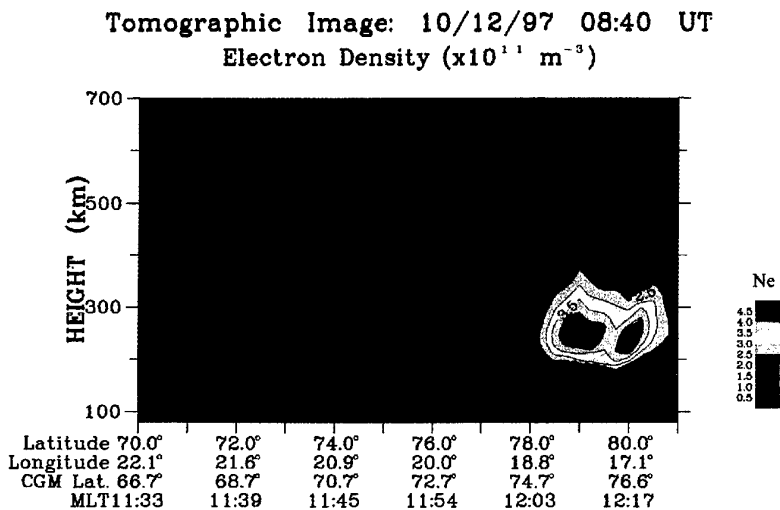


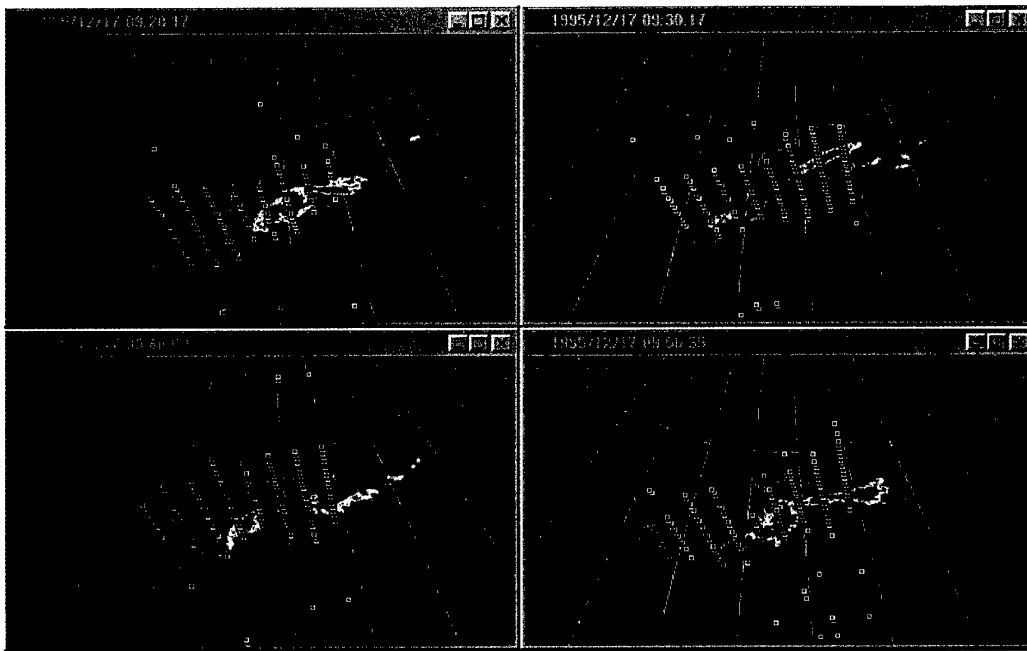
Figure 3. Tomographic image of electron density as function of height and latitude obtained from a satellite pass that crossed at 78° N at 0840 UT on 10 December, 1997.

In Walker et al. (1999) we described experimental observations of plasma enhancements in the electron density of the ionospheric F-region created by cusp/cleft particle precipitation at the dayside entry of the polar-cap convection flow. Measurements by meridian scanning photometer and all-sky camera of optical red-line emissions (type 1 aurora) were used to identify the latitudinally narrow bands of soft-particle precipitation responsible for structured enhancements in electron density obtained by radio tomography. Two examples were discussed in which the electron density features with scale sizes and magnitudes commensurate with those of particles were shown to be formed by precipitation at the entry region to the anti-sunward flow. In one case the spectrum of the incoming particles resulted in ionisation being created, for the most part below 250 km, so that the patch would persist only for minutes after convecting away from the auroral source region. However, in a second example as demonstrated by Figure

3, at time when the plasma density of the solar wind was particularly high, a substantial part of the particle-induced enhancement formed above 250 km. With the reduced recombination loss in the upper F-region, this structure likely retained the form as a patch during passage in the anti-sunward flow across the polar cap.

***Monitoring of the polar cap boundary location by radars:***

Regions of enhanced spectral width observed by coherent HF radars on the high-latitude dayside ionosphere are broadly used as an indicator of magnetosheath precipitation. The 2D morphology of coherent HF radar and optical cusp aurora has been studied for conditions of predominantly southward IMF conditions, which favours low-latitude boundary layer reconnection (Moen et al., 2000c). Despite the variability in shape of radar cusp Doppler spectra, the spectral width criterion of  $\geq 220 \text{ ms}^{-1}$  proved to be a robust cusp discriminator. For extended periods of well developed radar backscatter echoes, the equatorward boundary of the  $\geq 220 \text{ ms}^{-1}$  spectral width enhancement lined up remarkably well with the equatorward boundary of the optical cusp aurora. This is demonstrated in Figure 4 below.



**Figure 4.** Colour-coded (ranging from blue to red with increasing intensity) all-sky images of the 630.0 nm aurora for the period 0920.17 UT to 0950.35 UT on December 17, 1995. The auroral emission is mapped onto a geographical grid assuming an emission altitude of 215 km. The images have been cut at  $75^{\circ}$  zenith angle. The yellow squares mark positions of gates with spectral widths  $\geq 220 \text{ ms}^{-1}$  along CUTLASS Finland beams 5-11 from west to east. The 630.0 nm and spectral width boundaries are very similar in shape, even when the boundary is undulating or changing.

The spectral width boundary was, however, poorly determined during development and fading of radar cusp backscatter. Closer inspection of radar Doppler profile characteristics suggests that a combination of spectral width and shape may advance boundary layer identification by HF radar. For the two December days studied the onset of radar cusp backscatter occurred within pre-existing 630.0 nm cusp auroral activity and appeared to be initiated by sunrise, i.e. favourable radio wave propagation conditions had to develop.

Better methods were put forth for analysing optical data, and for physical interpretation of HF radar data, and for combining these data, as applied to detection, tracking, and better understanding of dayside aurora. The broader motivation of this work was to develop wider use by the scientific community, of results of these techniques, to accelerate understanding of dynamic high latitude boundary-processes.

We have also begun to validate use of the CP-4 mode of the EISCAT VHF radar at Tromsø to identify the cusp precipitation boundary. In the CP-4 mode the VHF radar is operated in a split-beam configuration looking north with a V-shaped field of view over Svalbard. In a work reported by McCrea et al. (2000) we compared EISCAT VHF with observations of the dayside auroral luminosity, as seen by the meridian scanning photometers at Ny Ålesund. We studied the ionospheric response to a ~1 hour interval of the interplanetary magnetic field (IMF) with variable  $B_z$  causing latitudinal movements in the cusp activity location. The cusp/cleft aurora was shown to correspond to a band of elevated electron temperatures in the VHF radar data. The electron temperature ( $T_e$ ) and the 630.0 nm boundaries were collocated and intimately following each other. It appears promising from these preliminary results that the polar cap boundary can be delineated from EISCAT radar observations of  $T_e$ .

## PERSONNEL

The key personnel in this project is:

Dr. Alv Egeland, Professor, University of Oslo

Mr. Espen Trondsen, Engineer, University of Oslo

Dr. Jøran Moen, Professor, UNIS, Svalbard

and graduate students at both UNIS and UiO.

Prof. Jøran Moen and his graduate students have been responsible for the observations at Longyearbyen, while the Plasma and Space Physics group at University of Oslo has carried out the campaign observations at Ny-Ålesund.

## REFERENCES AND PUBLICATIONS

**A new textbook relevant to this research project is under preparation:**

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## **INVITED TALKS AND LECTURES AT INTERNATIONAL MEETINGS AND RESEARCH INSTITUTIONS (1999- )**

Egeland, A., The main characteristics of dayside cusp aurora, guest lecture at NASA, Goddard Space Flight Center, Greenbelt, MD.

Egeland, A., The dayside cusp program at Svalbard: Dayside and polar cap cusp auroras and its regulation by IMF. Two guest lectures in Beijing and Shanghai, China.

Egeland, A., Auroral research on the next millennium: ESA PACK-meeting. 31 May – 3 June, 1999, Potsdam, Germany.

Egeland, A., and P. E. Sandholt, Dayside aurora characteristics during northward IMF, IAGA, Birmingham, UK, July, 1999.

Egeland, A., The history of Aurora up to the 19<sup>th</sup> century (invited talk), IAGA, Birmingham, UK, July, 1999.

Moen, J., Multi-instrument observations of cusp/cleft dynamics related to solar wind-magnetosphere interactions, Boston University, Center for Space Physics, January 21, 1999 (invited).

A. Egeland, and P. E. Sandholt: The IMF control of dayside aurora. The 27 European Optical Symposium, Stockholm, Sweden, 22-25 August, 2000.

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Moen, J., On the relationship between optical cusp aurora and coherent HF radar backscatter, National Institute of Polar Research, Tokyo, 10 February, 2000. (Invited)

Moen, J., Cusp/cleft activities observed by ground-based optics and HF coherent radar, Polar Research Institute of China, Shanghai, 11 April, 2000. (Invited)

Moen, J., Transient cusp auroral dynamics and ionospheric flow dynamics, Polar Research Institute of China, Shanghai, 11 April, 2000. (Invited)

Moen, J., Cusp/cleft activities observed by ground-based optics and HF coherent radar, Geophysical Center of WDC-D, Beijing, 14 April, 2000. (Invited)

Moen, J., H. C. Carlson, S. E. Milan, N. Shumilov, B. Lybekk, P. E. Sandholt, M. Lester, Dayside auroral activities and coherent radar backscatter, EGS 2000, Nice, 25-29 April, 2000 (Invited).

Moen, J., Studies of the polar cusp and cap by multi-instrument techniques; unresolved problems and future opportunities, Symposium on Space Research in the Polar Region in the next 25 years, The Norwegian Academy of Science, Oslo, 21 September, 2000 (Invited).