REPORT ON UK EISCAT RESEARCH IN 1996 AND 1997

Prepared on behalf of the UK EISCAT Community by

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<u>Cover Illustration</u>: The EISCAT Svalbard Radar, which began operations in March 1996, showing the buildings of Coal Mine Number 7 (partially obscured by the ridge) and the town of Longyearbyen in the distant background.

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1. Foreword

This report summarises the scientific highlights of the research programmes undertaken by the UK EISCAT community during 1996 and 1997. In addition, it includes the usual appendices providing details of the scientific papers including EISCAT results published during 1996 and 1997, the EISCAT campaigns organised in those two years and a list of the names and contact addresses of the entire UK EISCAT community. The report is intended to provide input to EISCAT's own two-yearly international report, to be published in summer 1998.

As usual, the last two years have been a very active period in the field of EISCAT research. On the positive side, the first successful operations of the EISCAT Svalbard Radar and the joining of Japan into the EISCAT Scientific Association represented major milestones in the evolution of the EISCAT Scientific Association. On the other hand, the explosion of Ariane 501 during the CLUSTER launch constituted a major reverse for many of our community whose work was set back by the failure of the mission. Nevertheless, the work reported in this report continues to bear testimony to the sterling efforts of UK scientists whose work has served to keep the UK EISCAT community at the forefront of international research in this area.

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2. Introduction

The structure of this report is intended to duplicate that of the equivalent report published two years ago. Some section headings have been changed to reflect the different research priorities which have been in evidence over the last two years. For instance, the inception of the ESR has meant that much greater importance has been attached to work on the cusp and in particular to the theoretical understanding of how reconnection processes affect the kinds of phenomena which can be produced in the high-latitude ionosphere. As well as the first observations made using the ESR, the inception of the CUTLASS radar has opened up new fields of study in high-latitude convection, F-region irregularities and the study of ULF waves. The use of heater-generated irregularities to provide scattering media for the CUTLASS signal has been a major new advance. This may have many interesting implications for future studies of the ionosphere by combining the techniques of incoherent and coherent scatter radar.

During the interval covered by this report, 56 papers by members of the UK EISCAT community have been published in refereed journals. This high figure is due in part to the appearance of two special journal issues featuring papers presented at EISCAT International Workshops; at Andenes, 1993 (in the Journal of Atmospheric and Solar-Terrestrial Physics, January 1996) and at Cargese, 1995 (in Annales Geophysicae, December 1996). The 1997 EISCAT International Workshop was held at the University of Leicester and again attracted a large number of papers involving UK authors. Many of these are currently going through the review process – a further 43 UK EISCAT papers are either submitted or in press. A measure of the continuing health of the community can be gauged by the fact that 8 PhD theses have been awarded in the UK for research work involving the EISCAT radar, demonstrating that EISCAT data continue to serve as a training ground for the development of new UK scientists.

Experimental work on the EISCAT radars has continued at a characteristically high level over the period of this report. In each of 1996 and 1997, the UK allocation of EISCAT time was used right up to the available capacity and on many occasions extra data have been secured by making pooled experiments in conjunction with other EISCAT Associate countries. A total of 10 campaigns were carried out during the last two years, during which 16 different UK experiments were run, representing a total of over 400 hours radar time. Many of these experiments formed part of international collaborations. Indeed, in the last two years UK scientists have collaborated with colleagues in every other country of the EISCAT Scientific Association, and several outside it. Experiments have included the first UK Special Programmes on the EISCAT Svalbard Radar, run in July 1997 as part of a campaign intended to combine studies of the cusp using radars and satellite tomographic techniques (see Section 9). A total of 28 UK scientists participated in campaign operations, of whom 10 were trainees. The continuing interest among new research students and RAs in running experiments at the radars is a further healthy sign of the enthusiasm that exists to exploit the facilities and the usefulness of the data.

3. Development of the EISCAT Radars during 1996 and 1997

Obviously the major event during 1996 and 1997 was the inception of the EISCAT Svalbard Radar (see cover picture), which carried out its first observations on 13 March 1996, and was officially inaugurated in a ceremony on 22 August 1996. The ESR is a 500 MHz radar located near Longyearbyen on Svalbard, with a fully-steerable 32m dish and state-of-the-art capabilities for data acquisition and signal processing. At the same time as the ESR became available, Japan entered the EISCAT Scientific Association in April 1996. Forty-two hours of test observations were run on the ESR during 1996, but the usage of the radar increased rapidly thereafter, with over 100 hours in the first four months of 1997. The initial data were all accounted as Common Programme. The ESR became available for Special Programme operations in July 1997. The early observations by the ESR were all field-aligned pointings using the GUP0 experiment, but the number of available experiment modes has slowly increased to include GUP1 (an experiment including alternating codes) and GUP2 (optimised for the topside). The first scanning experiment with the radar was carried out in March 1997 and although some teething problems were experienced, subsequent scanning experiments have proved to be highly reliable. Three Common Programmes for the ESR have been adopted with geometries similar to CP1, CP2 and CP3 at Tromso. A large amount of software has been developed both at EISCAT and in the UK (see Section 20) to enable the radar to be controlled and the data to be monitored during experiments. A software development contract between EISCAT and the UK included the provision of a UK consultant, Dr. Rob Dickens, who worked on Svalbard during the contract period, developing and implementing the UK software. The early ESR data show a number of interesting features, including asymmetric and highly time-variable spectra. Analysis software for the ESR data has been provided via a contract with Finland, which has led to the development of GUISDAP 2, a full-profile analysis program written in C++, which was demonstrated for the first time at a workshop in Toulouse in October, 1997.

Initially, the ESR transmitter was capable of only 500 kW peak power, but a contract with UK firm Harris Allied was signed in December 1996 to upgrade the transmitter power to 1MW. The additional transmitter modules were installed during the winter of 1997/98 and the first 1MW ESR experiments were carried out in February 1998. The decision has also been made to extend the EISCAT Svalbard Radar by the provision of a second antenna, and the process to choose the design and contractor for the building of the second dish is ongoing at the time of writing.

The development of the mainland radars during the last two years has been more limited, partly due to the fact that several EISCAT staff have been diverted into development work in support of the EISCAT Svalbard Radar. Work has, however, been done to renew the waveguide and rotary joint at Tromso where high reflected power has been a serious problem. Data transfer direct to the UNIX machines has been implemented at all sites and seems to be very reliable. A heater training course was held at Tromso in April 1997, and a Dynasonde data archive has been established on CD-ROM. A number of further tasks have been identified for the development of the mainland radar systems, but many of these have been thwarted by the unavailability of the necessary resources. The increasing age of some parts of the system has become noticeable during the last two years, but in general the mainland radars have still performed reliably. Budgetary pressures have forced savings to be implemented on insurance cover, power consumption and computer service contracts.

A number of administrative changes have occurred, with the EISCAT staff at Tromso having come under the aegis of the University of Tromso, and the Sodankyla staff now being employed by the University of Oulu. Dr. Jurgen Rottger's term as EISCAT Director ended on December 31st 1997. Dr. Tauno Turunen rejoined the EISCAT staff on 1st December 1997 and took over as Director on 1st January 1998. The proceedings of the 1993 EISCAT International Workshop at Andenes appeared in the Journal of Atmospheric and Terrestrial Physics in January 1996, and those of the 1995 EISCAT International Workshop at Cargese appeared in Annales Geophysicae in December 1996, partly explaining the large number of UK papers in that year (see Appendix A). A successful EISCAT International Workshop was held at the University of Leicester in July 1997. The next workshop is scheduled for September 1999 in Germany.

4. The Mesosphere and D-region

A significant new theory to explain the existence and phenomenology of PMSEs (Polar Mesosphere Summer Echoes) has been developed by Chaxel, 1997. This theory has produced predictions which can best be tested by combined UHF and VHF experiments during the period of changing conditions at either the beginning or the end of the PMSE season. Experiments aimed at confirming these theoretical predictions were carried out in June 1997 and and analysis of these data is presently under way. The ideas underlying the theory are being developed and tested out with a simple model of the ice-forming behaviour in a summer mesopause with tidal or other temperature oscillations present. Differences between UHF and VHF observations of the same PMSE layer, crucial to confirming the theory, are shown in Figures 1 and 2 (Chaxel and Aylward, 1997).

Another study of low-altitude scattering has examined mesospheric echoes recorded by the Dynasonde systems at Tromso and Halley Bay, Antarctica (Jones and Davis, 1998). The relationship of the mesosphere echoes seen by the Dynasonde with PMSE described above is unclear and the study sought to obtain more information on the Dynasonde echoes by comparing the occurrence statistics of the echoes seen at the two sites. It is clear that unlike PMSE, mesosphere echoes seen by both Dynasonde systems maximise in the winter months as shown in Figure 3. Mesosphere echoes do occur in the summer months at Tromso, though their occurrence frequency is reduced. No mesosphere echoes were seen at Halley Bay during the summer, possibly due to the lower sensitivity of the Halley system. There was no statistical evidence that the echoes seen in the summer were any different from those seen at other times of the year. However, only an intensive campaign of Dynasonde observations in conjunction with other radars which can observe PMSE would be capable of establishing whether the two phenomena are related.

The D-region has also been the subject of a study of the ion recombination rate, where EISCAT data has been compared to modelled values of the electron density profiles derived from the Sodankyla chemical model for a given input precipitation spectrum. While some profiles, especially during slowly-varying periods, can be well modelled with fairly simple precipitation spectra, it is not always possible to find an obvious match (del Pozo et al, 1997).

EISCAT VHF radar data recorded under CP-6 on a total of 31 days between June 1990 and January 1993 have been used to investigate the vertical winds associated with gravity waves at mesopause heights (Mitchell and Howells, 1998). The data reveal a motion field dominated by quasi-monochromatic gravity waves with representative apparent periods of ~ 30-40 minutes, amplitudes of up to ~ 2.5 ms^{-1} and large vertical wavelength. Figure 4 presents a set of time-height vertical-velocity contours for 31 July 1992 which display these typical characteristics. In some instances wave activity appears to be confined to particular height ranges of ~ 10 km or less and to have approximately Gaussian profiles of amplitude across that range - suggesting that the waves are ducted. An example of such a wave is evident at heights of ~ 78-88 km between about 07:00-12:00 UT in Figure 4. Plausible ducting mechanisms include structures in horizontal wind and/or temperature which could not be addressed with the CP-6 data considered here, and so further studies are to be carried out in the hope of confirming the presence of such ducts.

Vertical profiles of the vertical-velocity variance display a great variety of forms suggesting the waves are propagating in a complicated and changeable environment. There is little indication of the systematic wave growth with height expected for simple energy-conserving ascending waves. However, daily-mean variance profiles evaluated for consecutive days of recording show that the general shape of the variance profiles often persists over several days, indicating that properties of the background atmosphere are involved in shaping the vertical structure of the wave field. The mean variance evaluated over a 10 km height range (used as a crude measure of total wave activity) has values from 1.2 m^2s^{-2} to 6.5 m^2s^{-2} and suggests a semi-annual seasonal cycle with equinoctial minima and solsticial maxima, in agreement with MF-radar studies of horizontal winds at middle and high latitudes.

The mean vertical-wavenumber spectrum provides a powerful diagnostic of a number of proposed theories of gravity-wave saturation. Such spectra evaluated for the EISCAT data at heights up to 86 km have a mean slope, k, (spectral index) of -1.36 ± 0.2, consistent with observations made in the troposphere and stratosphere by other techniques, but disagreeing with the predictions of the linear instability, diffusive filtering and saturated cascade theories advanced to explain gravity-wave saturation, which suggest k values near -3, +1 to +1.8 and +1 respectively. The possible presence of a population of ducted waves is suggested as an explanation for the differences between theory and observation. The spectral slopes evaluated for individual days have a range of values, and steeper slopes are generally observed in summer than in winter. The spectra also appear to be generally steeper on days with lower mean vertical-velocity variance.

A major new addition to the instruments available to support EISCAT observations of hard particle precipitation has been the IRIS imaging riometer facility, which has been carrying out continuous observations of cosmic noise absorbtion in a region surrounding EISCAT since its inception in 1994. The range of topics which can be investigated by joint use of IRIS and EISCAT has been reviewed in a study by Collis and Hargreaves (1997). Most of the effort in comparative studies during the period of this report has been directed into four case studies of energetic precipitation events. These have each produced new scientific results and illustrated new possibilities for combining data from the two systems. Particular use was made of the technique of inverting observed electron density profiles to precipitating particle fluxes.

In daylight conditions on May 4, 1995, the spatial distribution and dynamics of the radio absorbtion showed a morphology similar to that of visible aurora at substorm onset, including spectral hardening. The VHF radar was pointed vertically, with the UHF tilted to intersect the D-region above Kilpisjarvi. The data from the two beams, separated by about 80 km in the D-region, showed some similarities, but also some differences (see Figure 5). The IRIS data allowed the EISCAT observations to be set in a proper spatial context with respect to the dynamical changes in the particle precipitation. These results gave further impetus to the need to combine IRIS and optical observations, ideally in combination with EISCAT data (Collis and Hargreaves, 1997).

An isolated region of energetic electron precipitation observed near local noon on March 1, 1995 was investigated using IRIS and EISCAT. IRIS revealed that the absorbtion event was essentially co-rotating with the Earth for about two hours. The spatial and temporal variations in the D-region electron density seen by EISCAT were interpreted in a consistent way when compared with the IRIS data. EISCAT detected significant increases in electron density at altitudes as low as 65 km as the event drifted through the radar beam. The altitude distribution of incremental radio absorbtion revealed that more than half of the absorbtion occurred below 75 km, with a maximum at 67 km. The energy spectrum of the precipitating electrons was very uniform throughout the event, and could be described analytically by the sum of three exponential distributions with characteristic energies of 6, 70 and 250 keV (Figure 6). A profile of effective recombination coefficient that resulted in self-consistent agreement between observed electron densities and those inferred from an inversion procedure was deduced. The observations suggest a co-rotating magnetospheric source region on closed dayside field lines. However, a mechanism is required that can sustain such hard precipitation for the relatively long duration of the event (Collis et al, 1996).

By itself, EISCAT furnishes spot measurements of the energy input within the radar beam. Broader-scale estimates require information on the spatial extent and lieftimes of the precipitation features, which is provided by IRIS. The daytime event occurring on May 31 1995 was rather weak. Although the radar detected this feature for about 10 minutes, the IRIS observations revealed that it was actually a long-lived, slowly equatorward-moving patch that drifted through the radar beam. More accurately, the precipitation showed co-rotating characteristics similar to those reported in the example above. With the assumption that the particle spectrum did not change significantly with time, which seems a reasonable inference based on the observations, the IRIS data could be readily converted into space-time maps of energy input for this event. Preliminary estimates for the main precipitation region were of order 10^6 Js^{-1}. The night-time substorm onset was very different from the daytime event. The precipitation expanded rapidly polewards across the IRIS field-of-view and showed very dynamic changes on time scales of a few seconds with very localised structure. The most intense absorbtion was slightly east of EISCAT, so the measured electron densities underestimated the maximum energy input. Knowing the absorbtion recorded by the IRIS beam closest to EISCAT, it was possible to estimate the maximum energy deposition by simply scaling the observed electron densities by the ratio of the two absorbtion measurements (implicitly assuming that the electron energy spectrum was the same). In this case the ratio was about 5, implying electron densities at the maximum some five times larger than observed by EISCAT. The implied peak energy was of order 10^8 Js^{-1}, which is considerably more than for the daytime event described above. The integral effects over event lifetimes are comparable because of the persistence of the daytime event (Collis et al, 1997).

A study of the above event is underway using data from all-sky TV, IRIS and EISCAT. Three auroral intensifications occurred in the TV zenith, separated by about 45 minutes each. The first of these did not break up, but the latter two did so. EISCAT showed an electric field enhancement during the first and third event, but not during the second one. The second and third events expanded polewards, passing through the EISCAT beam and allowing examination of the particle spectra. One topic in particular that is being addressed with these data is the co-location, or otherwise, of the visible aurora and the absorbtion regions. Preliminary results suggest that these are co-located during the pre-breakup phase, but that there is a delay (or spatial displacement) during the poleward expansion phase, with the absorbtion located in the wake of the visible forms.

In collaboration with Lancaster University, the group at the University of Sussex have been able to compare directly D-region absorption (as measured by the IRIS system at Kilpisjärvi) with co-located auroral activity (as recorded by low-light TV at Porojärvi). For the first time, the positions of the 49 IRIS beams have been accurately mapped onto the all-sky TV image, so that the auroral light intensity in each beam can be recorded as a time-series for cross-correlation with the IRIS data. In this way, the precipitation of electrons with energies of a few keV, which produce the aurora, can be spatially compared with the precipitation of electrons with energies of a few 10's of keV, which cause the D-region variations as monitored by changes in the absorption of cosmic radio noise. Newly-developed software is able to digitise the video record in near real time to achieve a time resolution of better than 0.2s for consistency with the IRIS system. Figure 7a shows snapshots of auroral activity from a sequence of three intensification events studied during an active 2-hour period on 19 November 1995. Figure 7b shows the simultaneous absorption and luminosity time-series for the 25 central beams of IRIS corresponding to another event on the same day.

5. Precipitation and Aurora

High-resolution studies of the small scale structure associated with auroral arcs has continued at the University of Southampton, combining EISCAT measurements, optical images and photometer measurements with theoretical work on auroral modelling. The latter has two strands which are being drawn together. The auroral model developed at Southampton incorporates the electron transport and ion chemistry that is involved in electron precipitation into the atmosphere. This continues to be refined to study the response of ion and electron temperatures to auroral precipitation. The other strand, which is the subject of a collaboration with Alaskan colleagues, tackles the mechanism in the inner magnetosphere responsible for the very narrow and dynamic elemental structures seen in the aurora.

Examples of the measurements that are combined in this work are shown in Figure 8. It contains two minutes of data when an ‘arc’ moved from south to north into the field of view of the radar and photometer (both aligned with the magnetic field), moved away again to the south, then advanced at a steady rate back through magnetic zenith and away to the north. This interval has been the subject of a detailed study, using modelling to investigate the changes in the electron density profiles as the precipitating flux underwent huge and sudden changes. It can be seen from the middle panel of the figure that very large and variable electric fields were measured during this event. This is also seen in the images of Figure 9, in which the horizontal electric field vectors for the time close to each image are superimposed. The images start during the first passage of the arc system. The largest electric field vector occurs in the third panel, which is sampled from an interval of several seconds when the arc was not in the radar beam. The field points towards the brightest part of the arc, where a fold in its length is present. The directions of the electric field vectors throughout this event are well correlated with the direction of the brightest part of the arc. It must be remembered that the vectors are at 3 s resolution, in which time the aurora changes greatly. Of significance is the interpretation of this sequence. Without the images, it would appear from Figure 8 that the largest field occurred inside an arc, at least judging from the electron density variations. Although the arc is not in the beam at this time, the electron density is unable to respond on these time scales. This work confirms earlier work (Lanchester et al., 1996) which found that the short term changes in electric fields were related to temporal variations within the nearby arc system.

It can be seen from the images of Figure 9 that the aurora in this case is not a single arc, but made up of two main bands, inside which there are several very fine elements. This can be seen in the narrow angle images of Figure 10, which are from the second passage of the arc through the radar beam (marked). Figure 11 shows the results of a full model run for this event lasting 10 s. The narrow elements are measured by the photometer (a) but the radar electron density measurements cannot respond to the changes which are smeared out (b). The modelled electron density (d) reproduces the measured density extremely well, but only by including as input an energy flux many times greater than the flux measured by the photometer (c). This verifies what is seen in the narrow angle images, that the elemental structures in the arc are much narrower than the photometer and radar fields of view, on average about 100 m in width. Contained in these are large energy fluxes, sometimes as great as 1 Wm^{-2}, which are found by modelling to be of monoenergetic electrons, embedded in a wider region of Maxwellian precipitation. The first evidence of this was found in a detailed study of data from the same campaign in January, 1995, shown in Figure 12 (Lanchester et al., 1997).

This discovery has direct consequences for the theoretical understanding of the origin of structured auroral arcs above the ionosphere and the mechanisms that produce field-aligned currents with such fine structure within the larger current system. The theoretical model of Otto and Birk (1994) is capable of producing thin arcs, as demonstrated in Lanchester et al. (1997). The 3-D simulation of magnetic shear in the lower magnetosphere generates the time evolution of field-aligned potential drop in 2 s as shown in Figure 13. The simulation is able to produce the field-aligned currents associated with this type of feature (Figure 14), consistent with the broader region of precipitation shown by the ionospheric model and optical observations. An image of an arc element with width of only 100 m and exhibiting small scale spirals in its length is shown for comparison in Figure 15.

The dynamic characteristics of energetic particle precipitation that we observe in optical images and in the response of electron densities measured by the radar imply an equally dynamic response in the plasma temperatures. Work in progress is aimed at modelling the evolution of electron and ion temperatures in response to particle precipitation with different spectral characteristics. The results should substantially aid the interpretation of temperature data acquired by the radar.

Implicit to all of the work undertaken at Southampton is the vital need for optical observations to complement the radar measurements. The campaigns of 1994 and 1995 were carried out in collaboration with MPI Garching, who provided the TV images from wide and narrow angle cameras, and the University of Oulu, who provided the photometers. Future work will involve collaborations in Svalbard with a new and exciting project to study proton precipitation. This will involve the development of a state of the art spectrograph, to measure the signature of the both protons and electrons in the cusp and near cusp regions at high resolution.

The same data as was used for the high time resolution study of auroral arcs was also employed for a comparison of ground and satellite data. The aim has been to compare data sets from EISCAT and satellites during the closest approach of the satellite to Tromso. This has been done using inversion alogorithms by which the spectrum of precipitating particles could be recovered from the EISCAT data or the EISCAT profile could be derived from the satellite data. The comparison has enabled these inversion techniques to be validated and an assessment made of the circumstanes under which it is appropriate to compare the two data sets. Two types of satellite data have been used, providing information on two different particle energy ranges. The DMSP satellites (DMSP-F10 and F12) predominantly measure soft electrons in an energy range from 30 eV to 30 keV. An electron transport code was used to estimate the ionospheric density profile which would be expected given the electron flux measured at the satellite. These estimates were compared with actual radar measurements and the results were found to be in close accord, particularly for periods such as that shown in Figure 16, when satellite imager data indicated that the precipitation was homogeneous and unstructured over a wide area (Anderson et al, 1997).

Conversely, the SAMPEX satellite measures only the most energetic part of the electron population (above 150 keV). These electrons should reach very low altitudes (~90 km) and EISCAT measurements made at these altitudes have been inverted to recover an estimate of the integral flux of the energetic particles which should have been measured at the satellite. The inversion was the first attempt to make use of a complex D-region chemical model developed by researchers in Finland and the UK for a comparison which would otherwise have been rendered impossible. Some very good agreements between the derived fluxes and the SAMPEX measurements have been found, particularly for close conjunctions. Data from the IRIS riometer system have also been used to investigate the structure of the regions of hard precipitation in order to validate the comparisons (del Pozo et al, 1998).

6. Ionospheric Conductivity and Collision Frequency

Simultaneous measurements by EISCAT, optical and riometer absorbtion images have been studied at the University of Lancaster to produce empirical maps of Hall conductance. It has recently been shown that it is possible to produce Pedersen conductance maps from optical images. This study will enable real-time global distributions of ionospheric conductivity to be constructed, and provide answers to questions involving the average energy and flux of precipitating magnetospheric particles. The optical emission measurements at 5577 nm made by the Digital All Sky Imager (DASI) give estimates of the precipitation patterns of soft electrons (<10 keV). The recordings of the cosmic radio noise absorbtion made by the Imaging Riometer for Ionospheric Studies (IRIS) at 38.2 MHz provide estimates of the energy spectra of the precipitation patterns of hard electrons (> 10 keV). With EISCAT measurements of the electron density profile, estimates of the energy spectra of precipitating particles can be made. Figure 17 illustrates the comparison of IRIS and DASI images for 13 February 1996, when EISCAT was running a CP1 experiment.

Estimates of the ion-neutral collision frequency are generally derived from the returned incoherent scatter signal through a spectral fitting technique, or equivalently from the autocorrelation function. Davies et al. (1997b) have proposed an alternative method, which permits the derivation of two independent estimates of collision frequency based on the effect of ion-neutral collisions on the direction of the ion velocity vector and the ion velocity magnitude. The technique is demonstrated using EISCAT common programme 1 observations from 3 April, 1992. During this period, the ionospheric electric field was enhanced over a five hour interval to values exceeding 100 mV/m. The effect of thermospheric motion is accounted for by the authors through the inclusion of a first-order estimate of the neutral wind derived from ion energy balance considerations. Derived values of the normalised collision frequency (the ratio of the ion-neutral collision frequency to the ion gyrofrequency) are consistent with predicted values, the latter being derived from the MSIS-86 model thermosphere and the IGRF magnetic field model (see Figure 18). This method can provide estimates of the ion-neutral collision frequency to far higher altitudes than can be retrieved from a conventional fitting technique. Above 110 km the effect of collisions on the incoherent scatter spectrum ceases to be significant, whereas their effect on the ion velocity, particularly in direction, is manifest.

7. E-region irregularities

The COherent SCATter (COSCAT) experiment has been employed to make continued observation of E-region plasma irregularities with EISCAT at magnetic aspect angles close to orthogonal. The temporal resolution of COSCAT observations was previously limited to 1 s by the minimum dump time of the EISCAT correlator. Following the work of Schlegel et al. (1990) a new high temporal resolution experiment (FASTCOSC) was developed for COSCAT and successfully run between the 7th and 14th March, 1997. Individual power profiles were recorded in consecutive locations in the correlator memory, which was dumped every 5 seconds. This procedure enabled coherent backscatter power to be measured at 12.5 millisecond resolution and a measurement of the full autocorrelation function to be made every 100 milliseconds. The FASTCOSC observations indicate that E-region UHF radar backscatter is dominated by individual scatterers that have lifetimes between 20 and 60 milliseconds. The FASTCOSC results, together with a synopsis of the COSCAT BCOS (Barker coded studies of the spatial distribution of irregularities) experiment, are fully described in Eglitis et al. (1997b).

8. F-region irregularities

One of the major areas of activity in UK exploitation of EISCAT during the last two years has been the use of simultaneous and co-located data from EISCAT and the CUTLASS HF radars. This pair of radars has a bistatic volume which overlaps with the viewing areas of both the EISCAT and ESR radars. The existence of metre-scale F-region irregularities is vital if backscatter is to be received by the CUTLASS radars. As such the existance of F-region irregularities is essential to all CUTLASS/EISCAT comparative work. For descriptions of work involving the combined use of the two radar systems see sections 10 (Ionosphere-Thermosphere Interactions), 11 (Artificial Heating) and 12 (ULF waves).

9. Large-Scale Ionospheric Structure

The major thrust of the research programme of the Radio and Space Physics Group at the University of Wales, Aberystwyth, has been the experimental study of geophysical mechanisms controlling the high-latitude ionosphere, with radio tomographic measurements complementing observations by incoherent scatter radars and optical techniques. A chain of satellite receiving stations has been established to the north of Scandinavia enabling images of spatial structures in electron density to be obtained routinely in the auroral, cusp and polar-cap ionospheres. The automatic receivers were deployed at Longyearbyen, Bjørnøya and Tromsø in the summer of 1996 adding to the system that has been operating at Ny-Ålesund since 1991. The system yields regular tomographic images of the electron density in a region of key importance to the understanding of the interaction of the solar wind and the magnetosphere/ionosphere system, which also covers the viewing areas of the EISCAT and ESR radars.

The most striking advance, made in the collaboration with Dr. Jøran Moen of UNIS has involved relating optical observations from all-sky camera and meridian scanning photometer instrumentation on Svalbard to electron density features seen in tomographic images. One case study in the daytime cusp sector shows, for the first time from ground-based instrumentation, the simultaneous ionospheric signatures of three characteristic features of a magnetopause reconnection event (Figure 19). A region of auroral-E ionisation can be identified with energetic electron precipitation from the central plasma sheet. This terminates at its northern edge at a boundary identified with that of closed/open field lines. To the north a steep gradient is found that leads to a field-aligned enhancement with a narrow structure extending into the high topside F-layer, probably linked to a field-aligned current. An upwards tilt in the height of the F-layer peak over a limited range of latitude to the north can be linked to the dispersion of the soft ions, precipitating on the poleward-convecting open flux-tubes. Signatures in the optical emissions, with a sharp equatorward edge to the red-line aurora and poleward moving forms, represent known characteristic features of magnetic reconnection and support the interpretation of the features imaged by tomography (Walker et al., 1998).

Another collaborative project with UNIS is addressing the relationship between electron density enhancements at both E- and F-layer heights and the structure of discrete auroral arcs in green- and red-line emissions respectively in the region 1 field-aligned current sector, after magnetic noon. Results from case studies have enabled the ionospheric signatures of the auroral precipitation to be identified. It has also been possible to calculate the different response times for the ionisation in the two height regions (Moen et al., 1998).

First results have been obtained linking a spatial image from ionospheric tomography to the temporal changes in electron density seen in an early run of the ESR radar (Mitchell et al., 1998). A spatially-narrow field-aligned enhancement in electron density, extending over a confined range in latitude, has been identified with a temporally-confined increase in plasma concentration measured by the radar (Figure 20). The interpretation of the observations has been aided by information on convection flows obtained from the CUTLASS HF radar system.

Images from the high-latitude chain have been used with EISCAT SP-UK-TOMO observations in a study of the dayside trough, a little understood feature of the high-latitude ionosphere (Pryse et al., 1998). Indeed, the only substantial previous work used ionosonde observations from IGY in 1957/8. The morphology of the quiet daytime trough has been established at the edge of the dusk convection cell in the post-noon sector. In a case study during disturbed geomagnetic conditions, the existence of the tongue of plasma feeding dayside photoionisation into the polar cap, predicted by modellers, has been demonstrated experimentally. Results from earlier studies have confirmed the existence of a polar hole of depleted plasma, convecting in darkness in the centre of the winter dawn cell (Pryse et al., 1997).

Research on the geophysical mechanisms responsible for trough formation has been carried out using observations, made at a time of extreme geomagnetic quiet, by the EISCAT radar operating in the SP-UK-BLOB mode (Jones et al., 1997). The results demonstrated unambiguously that the structure of the poleward wall of the trough is related to energy input from localised, transient soft-particle precipitation, characterised by latitudinally narrow, field-aligned bursts of enhanced electron temperature. The apparent equatorward advance of the trough wall follows as a dynamic response to the movements of the edge of this structured precipitation. This study demonstrated conclusively that the boundary blob surmounting the trough wall is not simply a reconfigured polar-cap patch, as had been suggested by a previous modelling study. The field-aligned nature of both the poleward wall seen in plasma concentration and the localised enhancements in electron temperature measured by the radar enable estimates to be made of the inclination of the geomagnetic field at F-layer heights above EISCAT. Values were obtained in agreement with those predicted by the IGRF90 model to within the error estimates.

A study has been carried out at Sheffield Hallam University in which the EISCAT Common Programme data has been searched systematically in order to find the simultaneous occurrence of high ion temperature and depleted electron density characteristic of a high latitude trough (Figure 21a,b). These features are believed to arise when frictional heating in a narrow convection channel acts to increase the recombination rate, which in turn depletes the F-region density. These software tools are now being used to search for similar high-latitude features in the data from the EISCAT Svalbard Radar. Although several hundred hours of data from the ESR now exist, the combined data set has not previously been used to search for particular geophysical features in a systematic manner.

10. Ionosphere-Thermosphere Interaction

Ion frictional heating constitutes one of the principal mechanisms whereby energy originating in the solar wind is deposited into the Earth's ionosphere and ultimately the neutral atmosphere. A recent paper by Davies et al. (1997a) documents a statistical study of ion frictional heating based on more than 4000 hours of observations from EISCAT UHF common programmes 1 and 2. The selection criterion adopted by the authors to identify intervals of frictional heating requires an enhancement in the field-parallel F-region ion temperature exceeding

100 K over two or more consecutive integration periods. This corresponds to a ion velocity of approximately 500 ms^{-1}. The diurnal distribution of ion frictional heating observed by EISCAT established by this method is subsequently classified according to the prevailing interplanetary magnetic field (IMF) orientation and geomagnetic activity. The results are interpreted with reference to corresponding distributions of enhanced ion flow. The orientation of the IMF profoundly influences the occurrence distribution of ion frictional heating (see Figure 22), for which an analogous effect on the distribution of enhanced ion velocities provides the explanation (see Figure 23). Under conditions of a negative z-component, the occurrence of frictional heating greatly exceeds that for a positive z-component. Further sub-classifying according to By reveals asymmetries in the proportion of ion frictional heating associated with the eastward and westward convection cells.

The data set collected during the Ion-Neutral Dynamics Investigation (INDI) now contains many hundreds of hours of simultaneous EISCAT and FPI data spanning a period of 13 years. Recent work has shown the value of the O^+-O collision parameter calculated from such data is very sensitive to the statistical methods employed. The most accurate method, that of Maximum Likelihood Analysis, requires a detailed analysis of the errors in all the parameters involved (Daniell et al, 1998). Over the past year, much work has been done to calculate these errors. Recent work at RAL has extended the previous work on estimating the O^+-O collision cross-section (which used momentum balance calculations) by using large amounts of EISCAT Common Programme data to make estimates of the same parameter using heat balance calculations.

Quasi-periodic fluctuations in the ground-scatter returns from the SuperDARN network of auroral HF radars have been associated with the passage of medium-scale atmospheric gravity waves. Arnold et al. (1997) have used data from the CUTLASS Finland HF radar to validate this capability experimentally. Variations in the range of the first significant power returns from the F-region have been shown to be a very sensitive indicator of gravity waves and this parameter has thus been adopted in the study. Figure 24a,b show a direct comparison of 15-60 minute waves in both the EISCAT and CUTLASS Finland radar data for March 1st 1995. Note that the former measures variations of electron density with height, whilst the path shape for the latter is the shallow horizontal arc made by beam number five pointing towards Tromso. Excellent agreement was obtained for an effective reflection height of 235 km. Further improvements were obtained by introducing a delay to account for the propagation time from Tromso to the CUTLASS first return. This allows the phase speed of the gravity waves in the EISCAT - CUTLASS direction to be inferred.

Spectral and wavelet analysis of spatially and temporally coincident time series of CUTLASS ground scattered power and EISCAT measurements of electron density and line-of-sight velocity have been undertaken at Sheffield Hallam University. This work has been supported by ray tracing simulations and has revealed a reasonable correlation between the observations from the two systems during the periods under consideration. Figures 25 to 27 show periodograms, a plot of the cross-correlation function and mean squared wavelet maps from one such period. The CUTLASS and EISCAT periodograms are very similar with significant peaks centred on 0.07 mHz and 0.17 mHz. The cross-correlation function peaked at 0.83 with ground scattered power lagging electron power by 6 minutes. The wavelet maps show similarities in the wavelet level centred on 0.18 mHz but are distinctly different at higher levels.

11. Artificial Heating

Extensive use has been made of the CUTLASS HF radars to study small scale field-aligned plasma density irregularities which are efficiently excited by the EISCAT high power HF facility during O-mode heating of the F-region. CUTLASS has proven an ideal tool for this purpose, since it is sensitive to irregularities with scale sizes of a few tens of cm across the geomagnetic field. Also, the Tromso site is within the field of view of both the Finnish and Icelandic radars which comprise the CUTLASS pair. A number of important new results have been obtained from experimental campaigns carried out during 1996/7.

Figure 28 illustrates an example of the first detailed study of the two-dimensional distribution of heater induced irregularities. These were mapped by the CUTLASS Finland radar, using a five beam scan with a 1 s dwell time in each pointing direction. Range resolution is 15 km and the beam widths correspond to distances of around 50 km at these ranges (1000 km). The heated region extends over 3 degrees of latitude and 6 degrees of longitude. This result is also important in establishing the threshold electric fields required to excite irregularities at the egdes of the heater beam. Thresholds are often less than 0.01 Vm^{-1} (Bond et al., 1997a).

Figure 29 illustrates two examples of the temporal decay of heater induced irregularities seen in CUTLASS backscatter from 25 April 1996. In the upper panel, backscatter from the irregularities falls below noise levels in less than 1 minute, whereas in the second panel the decay is not complete within 3 minutes. Preliminary results indicate that shorter decay times tend to occur close to midday (LT) and lengthen towards dusk. The data in the lower panel indicate that a two stage decay process is clearly evident as the decay times lengthen (Bond et al., 1997b).

The scatter in Figure 30 is from a comparison of CUTLASS and EISCAT tristatic measurements of the drift speed of heater induced irregularities. There is good correlation between the two forms of measurement indicating that, for these conditions at least, the artificially induced irregularities appear to drift with the background flow (Eglitis et al., 1997a).

The detailed data in Figure 31 illustrate the first observations of the interaction of heater waves with natural F-region radio aurora. Man-made radio aurora can be clearly observed in the intensity data in the upper panel, during the 'heater on' times (indicated by the data in the forth panel) in ranges between 850 and 1050 km of the Finland radar. Weak, natural aurora begin to appear in the farthest radar ranges just before 1600 UT, and then drift steadily towards the heater beam. A remarkable event takes place just after 1601 UT when a natural aurora comes close to the outer edge of the heater beam and is suddenly artificially enhanced by the high power radio waves. A similar thing happens just after the heater is turned on at 1604 UT. The differences in the speeds of the natural and artificial aurora are clearly illustrated in the velocity data in the second panel, and altitude differences can be inferred from the angle of arrival data in the third panel. The fifth panel indicates changes in the operating frequencies of CUTLASS and the heater, and also the peak plasma frequency, during the heating sequence.

During a recent heating campaign (April, 1997), artificially excited ULF waves from a heater modulated electrojet above Tromso were detected by sensitive magnetotelluric field meters which were deployed at Wick in Scotland (Figure 32, lower panel). This is the largest range (around 2000 km) over which heater induced ULF waves have so far been detected. The magnetic field times series (upper panel) and spectrum (centre panel) for waves of two minutes period, indicate field strengths higher than expected from simple dipole calculations, and could indicate some type of resonant response at Wick, where, as it happens, the field line resonance frequency is around 2 minutes.

12. ULF waves

The CUTLASS Finland HF radar has been operated in conjunction with the EISCAT Tromso HF ionospheric heater facility to examine a ULF wave characteristic of the development of a field line resonance (FLR) driven by a cavity mode caused by a magnetospheric impulse (Yeoman et al., 1997). When the heater is on, striating the ionosphere with field-aligned ionospheric electron density irregularities, a large enough radar target is generated to allow post-integration of the CUTLASS data over only 1 second. When combined with 15 km range gates, this gives radar measurements of a naturally occurring ULF wave at a far better temporal and spatial resolution than has been achieved previously. The time-dependent signature of the ULF wave (see Figure 33) has been examined. The wave evolved from a large scale cavity resonance, through a transient where the wave period was latitude-dependent and the oscillation had the characteristics of freely-ringing field lines, and finally to a very narrow, small scale local field line resonance. The resonance width of the FLR was only 60 km and this has been compared with previous observations and theory. The FLR wave signature is strongly attenuated in the ground magnetometer data. This leads to the characterisation of the impulse driven FLR being only very crudely achieved with ground-based diagnostics. An accurate determination of the properties of the cavity and field line resonant systems challenges the currently available limitations of ionospheric radar techniques. The combination of the latest ionospheric radars and facilities such as the Tromso heater can result in a powerful new tool for geophysical research.

Since the middle of 1995, an HF Doppler sounder has been running almost continuously in northern Norway. The Leicester Doppler Pulsation Experiment (DOPE), which consists of a receiver at Ramfjordmoen and a transmitter at Seljelvnes, facilitates high spatial and temporal resolution observations of the ionospheric signatures of ULF waves at high latitudes. Simultaneous operation of the EISCAT UHF radar in common programme (CP-1) mode has made it possible to study the ionospheric signature of a magnetospheric ULF wave (Wright et al., 1997). These are the first results of such wave signatures observed simultaneously in both instruments. Figure 34 demonstrates that the observed Doppler signature was mainly due to the vertical bulk motion of the ionosphere caused by the electric field perturbation of the ULF wave, thus achieving the first direct observational confirmation of a numerical simulation. The wave, which was Alfvenic in nature, was detected by the instruments

8 degrees equatorward of the broad resonance region. The implications for the deduced wave modes in the ionosphere and the mechanism producing the HF Doppler variations have been evaluated.

13. Magnetic storms and substorms

A major recent advance has been the theoretical prediction of a phenomenon which has become known as "substorm quenching" (Lockwood and Opgenoorth, 1997). This prediction came from the realisation that changes in the solar wind density can increase or nullify lobe field increases caused by excess magnetopause reconnection voltage. The sum of the solar wind thermal and dynamic pressures acts to compress the tail and so influences the magnitude of the lobe field and the cross-tail current. As a result, compression of the magnetosphere can trigger onset of substorm expansion phases at almost any point in a growth phase. A major decompression of the magnetosphere can quench the expansion phase. Recent observations confirm that this quenching can indeed occur and the signatures have been identified in a variety of observations used to monitor substorms. These include a major solar wind density increase seen by WIND, IMP-8 and GEOTAIL which impacts the magnetosphere immediately after a substorm expansion phase onset, a decompression of the magnetosphere seen by GEOTAIL, a quenching of the expansion bulge aurora, an unusual sudden end to geostationary injections, an onset of rapid convection inside the quenched bulge seen by EISCAT, and a decay of the lobe field at X= -28 R_E seen by INTERBALL which is quantitatively consistent with the solar wind density decrease. This newly identified phenomenon raises a host of interesting questions which will be addressed in future studies.

A key point about this effect is that it offers a means to differentiate between the two major mechanisms proposed for substorm onset, namely the current-disruption (CD) model and the near-Earth neutral line (NENL) model. The latter has recently been modified because onset signatures are now known to be considerably closer to the Earth than where the NENL has been seen to form. Figure 35 shows two schematics which illustrate these ideas and how the development of the decay in the aurora is different in the two models. For the CD model the aurora forms at the equatorward edge of the expansion bulge and propagates poleward as the decrease in the tail lobe field propagates away from the Earth down the tail. On the other hand, for the NENL model it forms at the poleward edge and propagates equatorward as the effect of the reduction in reconnection rate at the NENL propagates Earthward. In addition, the lag is longer for the NENL model and there are also differences in the predicted response of the ionospheric convection. Application of these tests on the first identified set of observations of a quenching event has shown them to be consistent with the NENL model and inconsistent with the CD model (Lockwood and Opgenoorth, 1997).

14. Reconnection and flux transfer

In collaboration with colleagues at the State University of St. Petersburg, researchers at the University of Sussex have modified the analysis of the 2D version of the time-dependent Petschek-type reconnection model. This model, which serves as a prototype for the more realistic (3D) geometries needed to describe the magnetopause and magnetotail current sheet, has been extended to include the reconnection rate self-consistently, rather than as an input parameter. This has proved successful to the extent that this parameter now only needs to be specified during an initial short (dissipation-dominated) interval. This 'kick' is necessary because, during the short initiation phase, Petschek's magnetohydrodynamic (MHD) wave mechanism has not yet come into effect; the MHD waves need a short period to propagate beyond the confines of the small diffusion region. Several case studies have been analysed with different 'kicks' and with the plasma conductivity held constant (an unrealistic assumption, but one imposed to simplify the computations). First results suggest that the most efficient energy release is through a series of pulses with asymmetric shapes. This tentatively confirms that reconnection is inherently time varying, with an initial rapid increase of the reconnection rate followed by a much slower decrease, as implied from observations of reconnection-associated phenomena in the solar and magnetospheric context.

To provide empirical data, which are essential to these investigations, the Sussex group have surveyed the Sussex database of all-sky camera observations of the nightside auroral ionosphere (publicly accessible as described in Section 19). Several intervals have been identified containing rapid poleward-moving auroral arcs, and a technique which allows indirect measurements to be made of the reconnection rate from the observed arc velocity has been applied. The optical data were analysed in conjunction with simultaneous EISCAT observations, to determine the plasma properties of the ionosphere (in particular the bulk plasma velocity) through which the arcs were moving. Significant differences were observed between the arc motion and the background plasma velocity, conforming to expectations of the arcs mapping to a near-Earth (<30 R_E) magnetotail reconnection line. With the reconnection rate variations inferred from the poleward-moving arcs as input, the newly extended reconnection model has been used to calculate the corresponding behaviour of the plasma conductivity. Although the intervals of poleward arc motions were often short (a few minutes or less), in several instances it was possible to discern an initial rapid decrease in the conductivity, followed by a slower increase.

Analysis has continued of the physics of Flux Transfer Events, which are one of the most exciting phenomena discovered by EISCAT to date. The analysis has been done by fitting ion data measured by satellites during FTE events with the two-Alfven-wave version of the RAL cusp model (described in Section 15). In this case the model was applied to much shorter distances from the X-line appropriate to the dayside magnetopause. The fits were found to work extraordinarily well in all plasma parameters and also to predict the field line rotations and the FTE in the correct places. In effect, these fits have shown that FTE signatues are simply partial passages of the satellite into an open low-latitude boundary layer (LLBL). This could be explained as either a temporary compression of the reconnecting magnetopause so that the LLBL is moved over the satellite or because a bulge in the reconnection layer has passed over the satellite: such bulges are expected to result from transient reconnection pulses. There has been considerable controversy about which of these two mechanisms causes FTE signatures. This is important because the statistics of FTE occurrence are such that the reconnection pulse theory leads to the conclusion that FTEs are responsible for the majority of the observed transpolar voltage, hence pulsed reconnection must be the dominant form. By careful analysis of the reconnection rate, researchers at RAL have been able to resolve this controversy and show that there is indeed a pulsed reconnection rate variation associated with each FTE. In addition they have provided the answer to a major puzzle about magnetopause FTEs, namely why they sometimes exhibit a core of excess particle pressure. This high-pressure core is well explained by the model; it results from the fact that field lines at the core have been opened for much longer than those draped over the core, so that there has been time for higher densities of magnetosheath ions to reach the satellite. Thus events without a core are simply those seen closer to the reconnection site that produced them.

15. The Cusp and Cleft

The last two years have seen a great increase of interest in the modelling of processes occurring at high-latitudes in the cusp and cleft regions. In part this is undoubtedly due to the advent of the ESR as a major tool for the observation of this part of the ionosphere, and an appreciable amount of work has been directed at simulating the kinds of phenomena, such as soft particle precipitation, which the radar should observe. The two-dimensional model of cusp precipitation developed at RAL has been used to investigate pulsed reconnection signatures and how they will appear to satellites following meridional and longitudinal orbits (Lockwood and Davis, 1996a). The model is found to be capable of explaining previous observations which, although very different, arise from pulsed reconnection at the magnetopause under the same conditions, the differences arising from the direction of the satellite path. The reconnection events were revealed to be sporadic in time, but not patchy in space, events being necessarily more extensive than the 3 hours of local time that the satellite was in the cusp region during the longitudinal pass. This result was very controversial at the time of publication, though later work has shown that these criticisms were invalid (Lockwood, 1996). The ability of the technique to measure an accurate reconnection rate was confirmed by tests using the model by Lockwood and Davis, 1996b. The model is currently the only one that can predict time-dependent changes in the cusp, and also reproduces observed ion steps seen simultaneously in both up-going and down-going ions by the POLAR satellite (Lockwood et al, 1997), leaving no doubt that the steps are caused by variations in reconnection rate. Predictions of cusp particle precipitation using the model are shown in Figure 36.

An alternative explanation of poleward-moving events seen in radar data proposed that such events are caused by changes in the Y-component of the magnetosheath field induced by compressions due to solar wind dynamic pressure. The RAL model has been used to demonstrate that this idea was not consistent with the sequences of images seen by an all-sky camera and the events seen by the EISCAT radars. However, the events were consistent with the effects of reconnection pulses.

The cusp model is based partly on the concept of how ions will react with the magnetopause Alfven wave. Data from the dayside magnetopause and from hybrid simulations have shown that the predictions of the model are remarkably accurate. The simulations show that two such waves should be produced by a magnetopause reconnection site. Previous theory has thus been generalised to allow for the effects of Alfven waves launched by the reconnection site and standing on the inner edge of the Low-Latitude Boundary layer, on the inflow from the magnetospheric side of the boundary. With this extension, the model reproduces observations remarkably well (Lockwood and Moen, 1996). This confirms that transient auroral events seen in the Low-Latitude Boundary layer are on open field lines and are due to pulsed reconnection (Moen et al, 1996). Lockwood et al, 1997, included effects of ion reflection from the two Alfven waves and showed that dayside precipitations are well explained as being on open field lines, rather than on closed field as previously supposed. This can explain a number of paradoxes which were never resolved by the old view of the magnetic topology. For example, it has been shown that the projection of the reconnection X-line can be longer than the cusp, so the application of a typical reconnection voltage does not cause excessive flow speeds through a narrow “throat”.

16. Convection

The drift velocity of an auroral arc with respect to the background convection flow, as indicated by F region plasma velocity, has been a topic of interest for several years. It is not straightforward to measure a unique drift velocity for an auroral feature, which often changes rapidly in appearance and in orientation. Neither is it straightforward to measure the convection velocity, which also varies rapidly in magnitude and direction. A search was therefore made at the University of Wales, Aberystwyth, of the whole EISCAT database to study cases where a simple arc was observed by the Finnish network of all-sky cameras drifting steadily without any major change in appearance or orientation while EISCAT was making appropriate measurements of F-region plasma velocity.

In each case, the position of the lower boundary of the auroral arc was plotted in latitude and longitude at 1-minute intervals and a straight line was fitted to each plot where appropriate. An example is given for a simple arc observed drifting equatorward over EISCAT on January 25 1993. Figure 37 plots the latitude of the fitted line versus time at four different longitudes. From these four curves it is possible to determine an average southward velocity with a standard error which automatically incorporates all errors introduced by changes in appearance or orientation of the arc.

In Figure 38a, the drift velocity of the arc is compared with the component of F-region plasma velocity in the same direction measured by EISCAT Common Programme CP1. It is clear that within the range of observational error there is no significant difference between the two velocities. Figure 38b shows the magnetometer for 1993 January 25 taken at Kiruna which indicates that the arc was observed during the growth phase of the substorm cycle.

Table I lists results from 10 cases where the optical and EISCAT data allowed the comparison to be made with adequate precision. The conclusion is that during the growth and recovery phases of the substorm cycle the drift velocity of the arc is close to the average background convection velocity. However, during the two cases where a simple arc was observed during the expansion phase, drifting steadily equatorward without major change in appearance or orientation, the drift velocity of the arc was substantially greater than the convection velocity. This appears to resolve the contradictory results previously reported.

17. The Solar Wind

Measurements of interplanetary scintillation (IPS) made by the Aberystwyth using EISCAT have continued to yield important results. Earlier work had confirmed that the solar wind has two distinct speeds at around 400 and 800 kms^{-1}. The fast streams are associated with the high latitude polar coronal holes and the low latitudes with the equatorial streamer belt. Recent work has studied the interaction of fast- and slow-streams when they occur at the same heliocentric latitude. In addition the technique has been extended to include measurements of the exact direction of the mid- and high-latitude solar wind, which in turn implies the direction of the interplanetary magnetic field.

When fast and slow streams in the solar wind occur at the same latitude, owing to solar rotation there are occasions when a region of fast flowing plasma emerges from the Sun behind a region of slow flow. As the fast stream overtakes the slow stream, a compression region forms at the leading edge of the fast stream, which eventually generates shocks at a point beyond the Earth's orbit. These well known phenomena are called co-rotating interaction regions (CIRs) and fully-developed CIRs have been studied by spacecraft. EISCAT IPS studies, however, have displayed a unique capability to study the early stages of a CIR, closer to the Sun.

Figure 39 shows an example where the cross-correlation function of the observations made at two sites are compared with a theoretical model to give values of the fast- and slow-stream velocities along the line of sight. The evidence for the presence of a CIR is two-fold:

i) the 'fast' speed is given as 578 kms^{-1} - slower than the usual value of 700-800 kms^{-1}.

ii) the ratio of the "scintillation weight" per unit volume of the slow and fast streams is only 1.4 - far lower than the typical value of ~10 which occurs because the slow stream is normally much denser.

These results indicate that the fast stream has been slowed down to an intermediate velocity and the density and turbulence of the fast stream have been greatly enhanced, as expected in a compression region.

Previously, the observations of CIRs closest to the Sun had been made by the Helios space probe at 70 solar radii. Helios saw well developed CIRs, but without the forward and reverse shocks seen further out. The use of EISCAT has allowed CIRs to be seen much closer to the Sun. Figure 40a,b,c show the observation of source 0431p206 on three days in May 1996 at three separate distances from the Sun. At 17.6 solar radii the fast stream velocity is 742 kms^{-1}, typical of a fast stream seen above a coronal hole. At 24.6 solar radii the fast stream velocity had fallen to 623 kms^{-1} and at 27.9 kms^{-1} it had fallen further to 507 kms^{-1}. This analysis seems to suggest that CIRs begin to form at distances beyond approximately 20 solar radii. However, the observations at these distances are in regions of strong scattering meaning that there is an increased uncertainty in interpreting the data. In the case shown in Figure 41, the weak scattering regime begins at approximately 25 solar radii and so it is possible to conclude with certainty that the CIRs begin to develop at this distance at least.

The maximum cross-correlation coefficient between the scintillations observed by two spaced antennas is a maximum when the two antennas lie in the same plane as the direction of flow of the solar wind. Observations are normally scheduled for such times on the assumption that this flow is exactly radial. However, when extended observations of interplanetary scintillation are made, so that the orientation of the baseline between the two sites varies significantly, the results provide strong evidence that maximum correlation corresponds to a direction of flow with a small but significant component that is non-radial. Figure 41 shows an example of how the maximum cross-correlation varies for different spacing of the antennas in the plane perpendicular to the radial. When a Gaussian curve is fitted to the data, it indicates that maximum correlation occurs for a perpendicular spacing of -9.8 km. This corresponds to a component of flow offset 1.5° away from radial in an equatorward direction.

Owing to the small size of the non-radial component, it was necessary to make a careful estimate of the random errors involved in the measurements and then use a Monte Carlo method to determine whether the apparent offsets were genuine or a result of random error. Out of eleven extended observations analysed so far, four show offsets of between 1° and 2° significant at 10% or less (i.e. with less than 10% chance that the result is due to random error) and in each case the offset is directed towards the equator. With the planned improvement in the noise temperature of the Tromsø antenna the error level in future will be lower. It is therefore predicted that many more measurements of this kind will establish the average flow direction of the solar wind in the meridional plane for mid- and high latitudes and at solar distances ranging from 20 to 100 solar radii. These measurements will, in turn, provide unrivalled information on the average direction of the meridional component of interplanetary magnetic field at these latitudes and solar distances.

18. Theory and modelling studies

Several studies have been carried out relating EISCAT measurements to the results of the UCL-Sheffield ionosphere-thermosphere model CTIM. This has involved investigations of specific periods (Schoendorf et al, 1996) as well as more general studies of long-term trends, seasonal and solar cycle variations (Schoendorf et al., 1996, Aruliah et al, 1996a, 1996b, 1997).

In the case studies, it has been shown that the input electric fields and particle precipitation patterns at high latitudes need only be moved small distances to have significant effects on the modelled behaviour. Virtually any EISCAT measurements can be simulated with the right combination of high-latitude inputs, though there is no guarantee that this will be a unique solution. The case studies have prompted a development of CTIM whereby a much more flexible scheme has been introduced for selecting and modifying the high-latitude inputs to find a match with the ionospheric response.

The work in previous review periods on the UCL FPI database which pointed to the equinoctial asymmetry found in thermospheric and ionospheric data (Aruliah et al, 1996a,b) has revealed further unexpected behaviour in long-term trends. In particular, it has been found that there is a solar cycle dependence of the electric field - that is, at the same Kp there is a different electric field behaviour at solar maximum and solar minimum (see Figure 42). This was hinted at in the way the thermospheric winds behaved with solar cycle, but the average ion velocities were then shown to have a similar trend, and a plausible explanation for this has since been modelled with the CTIM model (Aruliah et al, 1997).

Besides these long-term trend studies, the UCL group has also contributed to case studies of auroral phenomena and their connection to the solar-terrestrial interaction exemplified by travelling convection vortices (Luhr et al, 1997) and substorm morphology (Gazey et al, 1996).

EISCAT data have been used to validate the new tidal generation code in CTIM. An improvement on previous versions of CTIM has been introduced by making the lower boundary the input layer, and making the velocities, temperatures and pressures there self-consistent. This has given the model the ability to simulate tidal oscillations self-consistently at much lower levels than before – in fact at heights where EISCAT often sees strong tidal signatures. Muller-Wodarg (1997) has given some preliminary evaluations of the success of modelling the radar data and this work is continuing with more directed and specific studies. Included in this will be evaluation of the modelled strength of the propagation of planetary waves into the upper thermosphere.

The ionospheric signature of a Flux Transfer Event seen in the EISCAT radar data on 29 March 1992 (Figure 43) has been used as the basis for a modelling study using a new numerical model of the high-latitude ionosphere developed at the University of Sheffield (Balmforth et al, 1998). The evolution of structure in the high-latitude ionosphere is investigated. A localized velocity enhancement, of the type associated with FTEs, is added to the plasma as it passes through the cusp. This is found to produce a region of greatly enhanced ion temperature. The new model can provide greater detail during this event as it includes anisotropic temperature calculations for the O^+ ions. This illustrates the uneven partitioning of the energy during an event of this type. O^+ ion temperatures are found to become increasingly anisotropic, with the perpendicular temperatures being substantially larger than the parallel component during the velocity enhancement. The enhanced temperatures led to an increase in the recombination rate, which results in an alteration of the ion concentrations. Large upward fluxes are seen to transport plasma to higher altitudes, contributing to the alteration of the ion densities. A region of decreased O^+ and increased molecular ion concentration develops in the cusp. The electron temperature is less enhanced than that of the ions. Plasma is stored in the topside ionosphere and released several hours after the FTE has finished as the flux tube convects across the polar cap. This mechanism illustrates how concentration patches can be created on the dayside and modified as they proceed into the nightside polar cap.

19. Instrumentation and techniques

Following the award of a contract from RAL in July 1996, the Sussex Auroral TV Database has been considerably extended and improved. New features of the MATLAB viewing software include gain adjustment, and simpler reset and scrolling control. The digitised summary data from Sussex all-sky and narrow-angle (20° field-of-view) TV cameras now stretches back from the most recent EISCAT campaign (February 1996) to December 1986. This data is available on-line, along with the interactive MATLAB viewing programs, from the Sussex public ftp site at:

ftp.sussex.ac.uk (directory: /pub/Units/space_physics/aur_tv).

To complement the summary data, a new system has recently been set up to produce digital movies from selected intervals of auroral TV, which can be viewed on any Windows PC. This service is available on request, usually at short notice, as the system is able to digitise and compress in real time; further details can be found on the Sussex Web page at:

http://www.susx.ac.uk/physics/research/space/spghmp.htm.

Figure 44 is a PC 'screenshot' showing the digital movie player (in the foreground) and a corresponding MATLAB keogram behind. Frame size and rate can be chosen freely for the particular investigation. With a view to the permanent installation of UK optical instruments at both Tromso and Svalbard, the Sussex group is currently developing software for remote access of data and control/monitoring of cameras. Of particular interest is the ability to access 'live' auroral images via the internet during operational periods. A test system, using auroral TV recordings, is presently in place and can be viewed from the Sussex Web pages (address above).

An area of great importance for EISCAT work, particularly for studies carried out at high time resolution, is a knowledge of how random error in the EISCAT velocity data relates to Signal to Noise Ratio and integration time, as well as other parameters of the ionosphere and experiment design. This question has been studied using data from a special experiment in which identical data were measured simultaneously on six radar channels. This allowed the random error to be calculated by simply comparing the simultaneous measurements made on the six channels. Using this method, an extremely accurate characterisation of the random error was made under a range of conditions (Figure 45). A new formula was derived to generalise these results (Williams et al., 1997).

A review of the whole technique of incoherent scatter (McCrea and Lockwood, 1997) was written in the UK for inclusion in an ESA Ground-Based Sourcebook. This book contains a full directory of all ground-based STP facilities with details of the instruments, the techniques they employ and the access, processing and visualisation facilities for the data they produce. An important spin-off from the consideration of co-ordinating ground-based instruments with satellites was the development of a new technique for planning such co-ordinated observations and also for searching for past occurrences of a desired configuration (Lockwood and Opgenoorth, 1997). This thinking was originally employed in a web-based system designed for the planning of ground-based observations in association with CLUSTER. It is now being developed into a more general system with a graphical web interface that will be useful for a whole variety of ISTP satellite missions and ground-based facilities.

20. Development work for the EISCAT Svalbard Radar

A contract between RAL and EISCAT, originally signed in 1995, covered the development in the UK of five software modules to be used at the EISCAT Svalbard Radar. This contact was extended in 1997 to allow the development work to be completed and to create a UK consultant, Dr. Rob Dickens, who would be paid by EISCAT to work at the ESR developing and implementing the software for the remainder of the contract period. The five modules being developed under the terms of the UK contract were as follows:

(a) User Monitor and Control (UMC), a package which provides graphical and command line interfaces to the radar control systems. The package consists of remote clients and local server applications at the ESR, with appropriate security measures between them. The UMC implements commands via a Pre-defined Experiment Manager (PEM) with commands being sent from the UMC to the PEM via RPCs (Remote Procedure Calls). The package was developed at Leicester and the ESR by Rob Dickens.

(b) Analysed Data Visualisation (ADV). This is a package of IDL routines which allow the plotting of analysed radar data from files in NCAR format. The package is very flexible and is capable of representing multi-parameter analysed data in a wide range of styles (panel plots, profiles, scatter plots, timelines, fan plots etc.). Widget-based controls allow a variety of more advanced applications, such as the ability to zoom into a selected area of data, to compare data between different data files and easily to change parameters, colour scales, display formats etc. ADV can be used for the plotting of both archive and real-time data, and includes the ability to decode analysed data served via the World-Wide Web. The package was developed at RAL by Vip Davda.

(c) Archive and Catalogue (AC). This package is a windows-based tool for cataloguing data and maintaining a data archive. The system has the whole functionality needed for these tasks, including the ability to assign names to tapes, write and append data, produce archive and user copies and to maintain a full record of the status and location of data within the archive. The latest version of the software makes extensive use of Java applets. The package has been developed at RAL by Steve Crothers.

(d) Post-Integration (PI). The integration program is used to post-integrate ESR and EISCAT data for subsequent manipulation or analysis. It is a very flexible package, which allows the user to control very flexibly what data is integrated and the strategy which is used. The integration program is designed to work with the Raw Data Manager (RDM) software at the ESR to enable data integration in real time, though it can also be used for off-line applications. The latest version of the software also allows the screening of satellites or other anomalous data using statistical techniques. This package was developed at Leicester by Nigel Wade.

(e) Raw Data Visualisation (RDV). RDV is a package of IDL and X-based routines to allow the plotting of raw ESR data in a number of different formats e.g. line plots and colour coded plots of lag profiles, autocorrelation functions, and spectra. Signal, background and calibration can be represented, with the appropriate corrections done on each. The program obtains data from the PI package referred to above, and can therefore be used for both real-time and off-line applications. The latest version contains the ability to gate data by height and to combine data from different pulse schemes, though this ability is currently restricted to GUP0 data. The package was developed at Aberystwyth by Andrew Pagett, and subsequently at RAL by Paul Gallop.

21. Figure Captions

Figure 1 Electron density as a function of time and altitude, derived from the UHF radar. Regions of depleted density, known as “bite-outs”, are in blue. The colour scale for the top panel is shown by the contours on the bottom panel (the electron density is given in cm^{-3}).

Figure 2 A PMSE layer as a function of time and altitude observed by the VHF radar at the same time as the UHF observations in Figure 1. Intense PMSE are shown in yellow and co-incide with the electron density bite-out.

Figure 3 Annual occurrence histograms for Mesospheric Echoes measured by the Dynasonde in Halley Bay, Antarctica for 1993 (top panel), Halley Bay for 1994 (middle panel) and Tromso in 1994/95 (lower panel). The x-axis for the Tromso panel has been offset so that winter is in the centre of the graph.

Figure 4 Time-height contours of vertical velocity for data recorded on 31 July 1992. The motion field is dominated by quasi-monochromatic gravity waves with periods from 30 to 40 minutes.

Figure 5a Time series of EISCAT VHF data from the May 4th 1995 sharp onset event. Each plot covers 30 minutes. The heights are shown on each panel. The VHF antenna was pointed vertically.

Figure 5b As for Figure 5a, but for the EISCAT UHF radar. The altitudes differ slightly from 5a because of the geometry. The radar was pointing at an elevation of 46.8^o and azimuth 135^o.

Figure 6 Upper panel: Electron energy spectra inferred from EISCAT D-region electron density profiles. Full lines with circles correspond to spectra fitted to two measured profiles with the photo-ionisation removed (i.e. precipitation only). Analytical fits corresponding to a three-component distribution are shown by broken lines with crosses. Lower Panel: Radio absorption measured by four IRIS beams at the longitude of EISCAT. The separation between the beams is about 30 km in the N-S direction at 90 km altitude.

Figure 7a Snapshots from the Porajarvi all-sky TV showing the evolution of the three auroral intensification events recorded on 19 November 1995. In the first event (frames 1a to 1d), a stable auroral arc begins to form large-scale folds but retains its narrow arc structure. The other two cases (frames 2a to 2d, and frames 3a to 3d) show similar arc and fold structure initially but develop into full-scale auroral break-up events. Frame 1a has the locations of the 0dB-centres of the 49 IRIS beams marked by white circles.

Figure 7b Time series plots of D-region absorption (upper panels) as measured by the IRIS system, and auroral luminosity (lower panels) as recorded by all-sky TV, in the 25 central beams of the IRIS array. (See Frame 1a of Figure 7a for the mapping of the IRIS beams onto the all-sky field-of-view.) The two sets of curves generally show very similar features: i.e. peaks in absorption correspond well to peaks in luminosity even in the fine structure. This implies that the few-keV electron precipitation producing the aurora is generally collocated with the few-10's-of-keV precipitation causing the D-region fluctuations as monitored by IRIS. Note however that, in some beam locations, the absorption and luminosity peaks appear to occur at slightly different times. For example, the cross-correlation function (arbitrary units) of the absorption and luminosity curves in beam (1,1), in the sub-interval shown, indicates a distinct lag of approximately 1 minute which cannot be accounted for in terms of geometrical and timing uncertainties.

Figure 8 Top panel - Electron density profiles at 0.2 s resolution showing two passages of an arc system through the field-aligned radar. Middle panel - Horizontal electric field components at 3 s resolution measured at 278 km. The largest field at 21:05:42 UT is in SE direction. Bottom panel -Intensity of 427.8 nm emission rate in the field parallel direction.

Figure 9 A sequence of images from the wide angle camera at 21:05:36.0, 40.1, 43.7, 49.1, 53.0, and 21:06:00.0, 04.1, 07.9, 10.1 UT. North is to the right and east at the top. The horizontal electric field vectors (3 s resolution) are superimposed. The largest field (panel 3) has magnitude 600 mV m^{-1}.

Figure 10 Images from the narrow angle TV camera at 21:06:04.5, 06.0, 08.0 and 08.5 UT. The position of the radar and photometer fields of view is marked. The field of view of the camera is 38 km by 28 km at 100 km, with north to the right and east at the top.

Figure 11 (a) Measured 427.8 nm emission rate for 10 s during the second passage of the arc system. (b) Measured electron density at 0.2 s resolution during second passage of arc system. (c) Blue curve is the energy flux estimated from 427.8 nm emission rate as shown in (a). Green curve is the energy flux required to produce the electron density profiles shown in (d), which match the measured profiles well.

Figure 12 Comparison of measured electron density during the passage of an auroral arc (left-hand side) with modelled densities produced by a population of monoenergetic electrons embedded in a wider region of Maxwellian precipitation (right-hand side).

Figure 13 Time evolution of the field-aligned electric potential drop obtained with a 3-D simulation of magnetic reconnection resulting in a localised auroral acceleration region. The plots show a horizontal cut through the ionosphere at a height of about 600 km and are separated by 0.5 s in time.

Figure 14 Contours of field-aligned current density for time t = 1 s and t = 2 s, and arrows indicating the plasma velocity in a horizontal plane directly above the ionosphere as a result of the simulation.

Figure 15 Image from narrow angle TV with position of radar and photometer marked. The field of view is 38 x 28 km.

Figure 16 Upper panel: Comparison of electron density measured by EISCAT during a DMSP pass (normal lines) with the density reconstructed from DMSP particle measurements using an electron transport code (bold lines). Lower panel: DMSP image of Scandinavia taken during the pass, with crosses showing the locations of the satellite and radar at closest approach.

Figure 17 Comparison of imaging riometer (IRIS) data with optical data from a digital all-sky imager (DASI) for February 13th 1996.

Figure 18 Normalised ion-neutral collision frequencies derived from EISCAT observations of the ion velocity vector rotation (solid line) and the reduction in the velocity magnitude (dashed line) at 125, 117 and 125 km altitude, respectively. Modelled values are represented by a dotted line.

Figure 19 Tomographic image of electron density from December 14 1996, showing the possible ionospheric signature of a magnetopause receonnection event.

Figure 20 Upper panel: Electron densities obtained from the EISCAT Svalbard Radar on 10 October 1996. The enhancement in electron density occurring between 1307 and 1312 is of particular interest. Lower panel: Tomographic image of electron density for the satellite crossing at 70^{o}N, 3^{o}E at 1321 UT on 10 October 1996. A latitudinally narrow enhancement in electron density at 78^{o}N in the ionosphere to the West of Svalbard is a prominent feature.

Figure 21a Fan plot of EISCAT CP3 data from May 20th 1987, showing a high-latitude trough in electron density. Three sequential half-hour scans are shown.

Figure 21b As for Figure 21a, but showing the region of enhanced ion temperature responsible for causing the trough.

Figure 22 Variation of the diurnal distribution of ion frictional heating with the orientation of the y and z components of the IMF. The histogram represents the percentage occurrence of frictional heating as a function of universal time, with a bin width of 30 minutes, and the line plot indicates the number of observations of each half hour bin.

Figure 23 Variation of the diurnal distribution of enhanced ion velocities, i.e. those exceeding 500 m/s, with the orientation of the y and z components of the IMF; the format of the figure is identical to that of Figure 22. Light grey shading indicates velocities with a westward zonal component, dark grey indicates those with an eastward zonal component.

Figure 24 (a) Electron density profile from EISCAT CP-1 on March 1st 1995 between 06:00UT and 18:00UT with a 15-60 minute band pass filter applied. (b) Variations in the distance to the first return from the Finland CUTLASS radar for the same interval applying a 15-60 minute filter. The beams rotate in a clockwise fashion from west to east of Tromso with beam 5 pointing directly towards it.

Figure 25 (a) Lomb periodogram of detrended ground scattered power from CUTLASS, compared with a similar periodogram of detrended EISCAT electron density (b) The two periodograms are very similar with peaks centred on 0.07 and 0.17 mHz.

Figure 26 Cross-correlation function of CUTLASS ground scattered power against EISCAT electron density. The function peaks at 0.83 with ground scattered power lagging electron density by 6 minutes.

Figure 27 (a) Results from a wavelet analysis of variations in CUTLASS ground scattered power, compared with a similar analysis of variations in EISCAT electron density (b) The wavelet maps show similarities centred on 0.18 mHz, but are distinctly different at higher levels.

Figure 28 The map on the left depicts the locations and fields-of-view of the CUTLASS and EISCAT radars. The shaded region indicates the area covered by the spatial plots presented in (a) and (b). (a) Returned power from the CUTLASS Finland radar on 26 April 1996, during a heater-on period. (b) As for (a), but showing returned power during a heater-off period.

Figure 29 Examples of heater-induced plasma irregularities as observed by the CUTLASS Finland radar. Top panel: backscatter power measured by CUTLASS Finland along beam 5 from 1404 to 1410 on 25 April 1996. Centre panel: as for top panel but for 1712 to 1718. Bottom panel: backscatter power measured by CUTLASS from 1712 to 1718 on 25 April 1996 for beam 5 and range bin 32. The dotted lines are 2 exponential functions fitted to the data after heater off.

Figure 30 Graph of the resolved component of the plasma drift velocity determined from EISCAT measurements against the irregularity phase speed of artificial field-aligned irregularities detected by the CUTLASS Finland radar.

Figure 31 Observations of artificial and natural plasma irregularities observed by CUTLASS Finland on 24 April 1996. Depicted are the CUTLASS measured backscatter power (top panel), irregularity phase speed (second panel) and elevation angle (third panel). The modulation of the heater (fourth panel) is monitored by an independent receiver and the bottom panel depicts the heater, plasma and CUTLASS frequency for the period of observation.

Figure 32 Magnetotelluric data taken from experiments run on 21 April, 1997. The top panel illustrates magnetotelluric measurements made at Wick before, during and after a period of artificial modification. The centre panel is a plot of the spectral panel during heating. The locations of the ionospheric modification facility near Tromso, Norway and the Short Period Automatic Magnetotelluric equipment in Wick, Scotland are included in the lower panel.

Figure 33 An overview of the radar and magnetometer data during the interval of heater-induced backscatter. A colour scale representation of the Finland line-of-sight velocity data is given in the top panel (positive velocities are towards the radar). Patches of radar backscatter are observed during periods when the Tromso ionospheric heater is operational (marked with vertical dashed lines). The second panel plots a time series for a single range gate, gate 31, which overlies the Tromso magnetometer. Filtered (150 - 50 s, 6.67 - 20 mHz) and unfiltered X and Y component magnetic field measurements are presented in the lower four panels. A correlated ULF wave signature can be seen in data from both instruments.

Figure 34 Velocities derived from DOPE (a) O-mode and (b) X-mode signals and (c) the vertical component of the northward field-perpendicular velocity measured by EISCAT for the interval 11.00-11.40 UT on 13th February 1996. Data have been filtered to exclude periods outside the range 30-400 s (a,b) and 120-400 s (c). In each case the ordinate axes display relative scales.

Figure 35 Schematic illustration of the concept of substorm quenching, applied to two rival models of substorm expansion onset, namely the synthesised current disruption model (CD, left) and the modified near-Earth neutral line model (NENL, right).

Figure 36 Observed and modelled cusp and mantle ions as seen in the magnetosphere by the POLAR satellite on 20 May 1996. The top two panels are for down-going solar wind ions and the lower two panels are for the simultaneously observed up-going ions. The sawtooth nature of the spectrograms results from pulsed magnetic reconnection. The test shows that the open model of solar wind injection and transport in the cusp region, developed at RAL is correct and that the reconnection rate is indeed pulsed when these stepped or sawtooth signatures are seen in the cusp dispersion ramp.

Figure 37 Drift of an arc in latitude at four different longitudes on January 25 1993 between 1857 and 1907 UT.

Figure 38 (a) Comparison of arc drift velocity (indicated by broken line) and plasma velocity in the same direction (indicated by a dotted line) for January 25 1993. (b) Magnetogram from Kiruna (67.9°N, 20.4°E) for January 25-26 1993.

Figure 39 The auto and cross correlation functions of the power spectra from an observation of source 0603p219 on 970616. The dotted line represents the data and the solid line represents the fitted curve. The model fits two velocities owing to the bi-modal nature of the solar wind. In this case the fast stream is estimated at 578.2 km/s; rather slower than the 800 km/s that would be expected from a high latitude fast stream.

Figure 40 Three observations of the source 0431p206 made on 22nd (a), 23rd (b) and 25th May 1996 (c). On each successive day the source appeared closer to the Sun and the fast-stream velocity increased. This suggests that the closest observation was of an undisturbed fast stream which at greater solar distances slows because of interaction with a slow stream.

Figure 41 A plot to show how the correlation of the signal between the two sites varies as the baseline perpendicular to the direction of radial flow changes during the observation. A curve has been fitted which has a peak that is offset from zero by around 10km, indicating an off-radial component in the flow of the solar wind.

Figure 42 Plot showing the difference between plasma flow patterns at solar minimum and solar maximum for various seasons of the year.

Figure 43 Plasma velocities showing the ionospheric signature of a Flux Transfer Event, as observed by EISCAT during the SP-UK-CONV experiment of 29 March 1992.

Figure 44 Showing the default size digital movie window (at upper right) during replay on a Windows 95 PC using the resident Media Player software. The screen resolution is 640 x 480 pixels in 65,536 colours. Media Player's controls (the window at centre right) allow great flexibility in playing and/or stepping the movie, and examining individual frames in detail. The background window (left and centre) shows the corresponding keogram plot using the MATLAB software provided on the database to view the summary data files. Control buttons along the lower edge of the window provide various functions which allow the user to scroll through the data, to zoom in on regions of interest, and to adjust the gain. Digital movies are available on request, usually at short notice, and should provide a valuable middle stage between the keogram summary plots and full video copy tapes.

Figure 45 Upper panel: Relationship between the predicted and the observed values of the rms error in measuring the plasma velocity (data analysed by the "full-fit" method). Lower panel: Relationship between the individual errors quoted by the EISCAT analysis program and the values derived by the theoretical formula.

Appendix A: Papers produced by the UK EISCAT Community

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Appendix B: UK EISCAT campaigns in 1996 and 1997

Campaign 45

Experiments From:	12 February 1996 – 23 February 1996			
Campaign Team:	Ian McCrea	RAL	Tromso	Campaign Manager
	Francis Sedgemore	Aberystwyth	Tromso	
	Jackie Schoendorf	UCL	Tromso/Kiruna	
	Andrew Hart	Leicester	Tromso	Trainee
	Peter Smith	Sussex	Tromso	Optical Support
	Alan Aylward	UCL	Kiruna	
	Graham Holdsworth	Leicester	Sodankyla	
Hours Used:	IRIS	30		
	UFIS	12		
	CUTL	15		
	DYNA	18		
	INDI	11		
	Testing etc.	6		
	TOTAL	**92**		

Campaign 46

Experiments From:	12 April 1996 to 5 May 1996			
Campaign Team:	Steve Crothers	RAL	Tromso	Campaign Manager
	Gary Beard	Aberystwyth	Tromso	Trainee
	Paul Eglitis	Leicester	Tromso	
	Sarah Woodall	Sheff. Hallam	Tromso	Trainee
	Darren Wright	Leicester	Tromso	
	Tim Yeoman	Leicester	Tromso	Trainee
	Giles Bond	Leicester	Kiruna	
	Paul Gallop	RAL	Kiruna	
	Carlos del Pozo	Aberystwyth	Sodankyla	

Hours Used:	IPSS	0.2
	HEAT	27
	COSC	13
	CUTL	3
	DOPE	20
	Testing etc.	2
	TOTAL	**65.2**

Campaign 47

Experiments From:	August 14 1996 to August 31 1996			
Campaign Team:	Phil Williams	Aberystwyth	Tromso	Campaign Manager
	Craig Varley	Aberystwyth	Tromso	
	Carlos del Pozo	Aberystwyth	Tromso	

Hours Used:	CUTL	16
	DYNA	12
	IPSS	2.4
	TOTAL	**30.4**

Campaign 48

Experiments From:	December 11 1996 to December 20 1996			
Campaign Team:	Vip Davda	RAL	Tromso	Campaign Manager
	Jackie Schoendorf	UCL	Tromso	
	Ian McWhirter	UCL	Kiruna	FPI Support
Hours Used:	INDI 14	(Of which 10 hours was charged to Germany)		

In addtion, a further 17.4 hours of IPSS time was used outside the periods of the campaigns listed above.

The total UK usage of EISCAT in 1996 was 220 hours (27% of the SP time).

Campaign 49

Experiments From: January 12 1997 to January 15 1997

Campaign Team: No UK personnel were involved. The UK experiments were runs as part of a Finnish campaign by a Finnish campaign team, and time was shared between UK and Finland.

Hours Used:	ARCS	2
	IRIS	2
	TOTAL	**4**

Campaign 50

Experiments From:	February 2 1997 to February 11 1997			
Campaign Team:	Alan Aylward	UCL	Tromso	Campaign Manager
	Eoghan Griffin	UCL	Kiruna	FPI Support

Hours Used:	INDI	11
	Testing etc.	2
	TOTAL	**13**

Campaign 51

Experiments From:	March 6 1997 to March 13 1997			
Campaign Team:	Ian McCrea	RAL	Tromso	Campaign Manager
	Nick Mitchell	Aberystwyth	Tromso	Trainee
	Vikki Howells	Aberystwyth	Tromso	Trainee
	Paul Eglitis	Leicester	Kiruna	
	Carlos del Pozo	Aberystwyth	Sodankyla	

Hours Used:	TIDE	27	(of which 9 hours were charged to UK)
	IRIS	20	
	EPEA	12	
	COSC	4	
	TOTAL	**63**	(of which 45 hours were charged to the UK)

Campaign 52

Experiments From:	April 19 1997 to April 30 1997			
Campaign Team:	Ian McCrea	RAL	Tromso	Campaign Manager
	Farideh Honary	Lancaster	Tromso	
	Giles Bond	Leicester	Tromso	
	Craig Varley	Aberystwyth	Tromso	
	John Gauld	Leicester	Tromso	Trainee
	John Storey	Leicester	Tromso	Trainee
	Hina Khan	Leicester	Tromso	Trainee
	Darren Wright	Leicester	Tromso	Heating Support

Hours Used:	HISI	12	
	HEAT	24	
	PLAR	11	
	IRIS	4	
	TOTAL	**51**	(+10 hours contributed by Germany)

Campaign 53

Experiments From:	9 June 1997 to 14 June 1997			
Campaign Team:	Alan Aylward	UCL	Tromso	Campaign Manager
	Andy Breen	Aberystwyth	Tromso	
Hours Used:	PMSE 24			

Campaign 54

Experiments From:	30 September 1997 to 13 October 1997			
Campaign Team:	Paul Eglitis	Leicester	Tromso	Campaign Manager
	Darren Wright	Leicester	Tromso	
	Peter Chapman	Leicester	Tromso	Technical Support
Hours Used:	HEAT 31	(of which 16 accounted to Germany, 15 to UK)		

Campaign 55

Experiments From:	24 November 1997 to 12 December 1997			
Campaign Team:	Vip Davda	RAL	Tromso	Campaign Manager
Hours Used:	ROCK	4		
	Testing etc.	4		
	TOTAL	**8**		

In addition, 21 hours of UK time were accounted to IPSS observations and Special Programme runs at the ESR.

<u>The total UK usage of EISCAT time in 1997 was 181 hours (20% of EISCAT SP time)</u>

APPENDIX C: THE UK EISCAT USER COMMUNITY

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