OPPORTUNITIES FOR MAGNETOSPHERIC RESEARCH WITH COORDINATED CLUSTER AND GROUND-BASED OBSERVATIONS

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Abstract. ESA's first multi-satellite mission Cluster is unique in its concept of 4 satellites orbiting in controlled formations. This will give an unprecedented opportunity to study structure and dynamics of the magnetosphere. In this paper we discuss ways in which ground-based remote-sensing observations of the ionosphere can be used to support the multipoint *in-situ* satellite measurements. There are a very large number of potentially useful configurations between the satellites and any one ground-based observatory; however, the number of ideal occurrences for any one configuration is low. Many of the ground-based instruments cannot operate continuously and Cluster will take data only for a part of each orbit, depending on how much high-resolution ('burst-mode') data are acquired. In addition, there are a great many instrument modes and the formation, size and shape of the cluster of the four satellites to consider.

These circumstances create a clear and pressing need for careful planning to ensure that the scientific return from Cluster is maximised by additional coordinated ground-based observations. For this reason, the European Space Agency (ESA) established a working group to coordinate the observations on the ground with Cluster. We will give a number of examples how the combined spacecraft and ground-based observations can address outstanding questions in magnetospheric physics. An online computer tool has been prepared to allow for the planning of conjunctions and advantageous constellations between the Cluster spacecraft and individual or combined ground-based systems. During the mission a ground-based database containing index and summary data will help to identify interesting datasets and allow to select intervals for coordinated studies. We illustrate the philosophy of our approach, using a few important examples of the many possible configurations between the satellite and the ground-based instruments.

1. Introduction

Long before satellites were even considered as feasible diagnostic tools for near-Earth space physics, networks of ground-based instruments have been utilized to gain an initial understanding of our closest space environment. Being remote-sensing observations, they are of lower resolution than *in-situ* data, and can at times be more difficult to interprete. Nevertheless, many of the still-discussed processes within the solar wind - magnetosphere - ionosphere system were discovered and initially understood with the help of distributed networks of ground-based instrumentation. Two of the most outstanding discoveries (predictions) of truely magnetospheric processes from the ground were the claim for the existence of

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field-aligned currents by Birkeland (1913), and the deduction of the magnetopause currents by Chapman and Ferraro (1931). Both of these were based on ground-based magnetometer recordings. Also the existence of the ionosphere, the basic morphology of the polar magnetic and auroral substorms, and other features of magnetospheric energy storage and release have been clarifed by ground-based observations, long before *in-situ* satellite measurements allowed us to understand the details of the underlying physical mechanisms in the magnetosphere.

Much of the progress in space science was made due to a well balanced parallel development of ground-based and satellite-borne instrumentation; series of individual discoveries cross-fertilized both methodological approaches. An early example of this was the discovery of the cusp/cleft region of magnetosheath-like particle precipitation, now one of the main objectives of te Cluster mission. A region of dayside auroral luminosity, dominated by red line (630.0 nm) emissions, was first reported by Sandford (1964) using ground-based optical observations. Eather and Mende (1971) used the ratio of the emission intensities at different wavelengths to show that this was caused by relatively soft electron precipitation. In the same year, Heikkila and Winningham (1971) and then Frank (1971) reported *in-situ* satellite observations of magnetosheath-like plasma precipitation in the magnetosphere, the association with the red-dominant aurora being first made by Heikkila (1972). In the recent past many new results have been achieved by planned coordinated observations both from the ground and in space during the same event or within the same spatial structure (see below for many more examples of such types of studies).

Most of the classical ground-based observational techniques are still actively in use today, however, spatial coverage, temporal resolution, instrument sensitivity and accessibility of data have been improved in phase with the technical revolution of space-borne instrumentation. Dense networks of magnetometers, standard and imaging riometers, digital ionosondes and optical cameras and photometers are operated in key regions of the northern hemisphere (with extreme concentrations in Fenno-Scandinavia, Canada, Alaska, and Greenland) and all over the Antarctic continent. All instruments in these networks provide data almost continuously. Optical instruments, e.g., can reveal transient events and track evolving boundaries, and the other network instruments have important applications, including monitoring the latitude of the auroral oval as well as the extent and intensity of disturbances along it (see examples below).

Modern radar technology has opened a wide and exciting field of sophisticated remote sensing measurements of the ionosphere. Radar systems operating at HF and VHF frequencies are sensitive to auroral backscatter from ionospheric irregularities, which drift under the influence of magnetospheric convection electric fields. Bi-static multibeam or scanning coherent radar systems can provide vital 2-dimensional snapshots of the convective flow in the ionospheric F and E region (Hanuise *et al.*, 1993). The SuperDARN network of HF radars, which is now to large part constructed and under operation (Greenwald *et al.*, 1995), can image such flow patterns over a very large fraction of the high-latitude region in the northern hemisphere. Also in the southern hemisphere, a tri-static HF system covering most of Antarctica is being built. The combined system will be unique in its possibility for conjugate studies and will provide an ideal monitor for the dynamical development of magnetospheric assymmetries, during different states of solar wind coupling. In Figure 1 (from Greenwald *et al.*, 1995) we show what spatial coverage of coherent radar systems can be expected for the years of the Cluster mission.

In terms of the number of geophysical parameters measured, the most powerful of the ground-based observatories are the incoherent scatter (IS) radars, which, for example, can be used to measure ion drifts (electric fields), ion and electron temperatures and plasma density throughout all ionospheric layers. With models and complex processing, these radars indirectly yield much more information, including conductivities, neutral winds and precipitating electron spectra. By the time Cluster data-taking commences in 1996, the EISCAT Svalbard Radar, ESR (Cowley *et al.*, 1990) will be in operation on the island of Spitsbergen and this will add to the existing high-latitude IS facilities at Söndre Strömfjord, Millstone Hill, and EISCAT.

The range and flexibility of these radars allows detailed measurements to be made which will be valuable complements to the Cluster observations. However, while most of the earlier mentioned instrument networks operate more or less on a permanent basis (data availibility will only be limited by instrument failure, cloud coverage, and excitation level of ionospheric instabilities, respectively), incoherent radars have limited hours of operation. IS radars require much maintenance, and hardware degradation and power consumption are too expensive to allow operation on a continuous basis. The complexity of the radar systems and in addition the complicated transmission and reception schemes require real-time operator monitoring and supervision of both hardware and software. Furthermore, IS radars usually require large antenae, which are generally steered mechanically. This limits the speed with which the beam can scan across the ionosphere, and calls for careful experiment design to balance the requirements of spatial coverage and time resolution.

Therefore detailed planning is required to ensure that the best opportunities for combined studies with Cluster are exploited. To start with it will be important to match the radar operating modes to the satellite observations, such that the radars genuinely add to the information that the satellites obtain. For example, in order to achieve the right balance between spatial coverage and temporal resolution, antenna scanning patterns appropriate to different conjunctions between the spacecraft and the radars will have to be designed. Similarly, the right balance between spatial and temporal resolution will need to be struck by the pulse coding scheme. For example, for most applications two major antenna pointing geometries of the combined EISCAT UHF, VHF, and ESR radar systems appear to be sufficient and effective. When Cluster crosses field lines connected to the

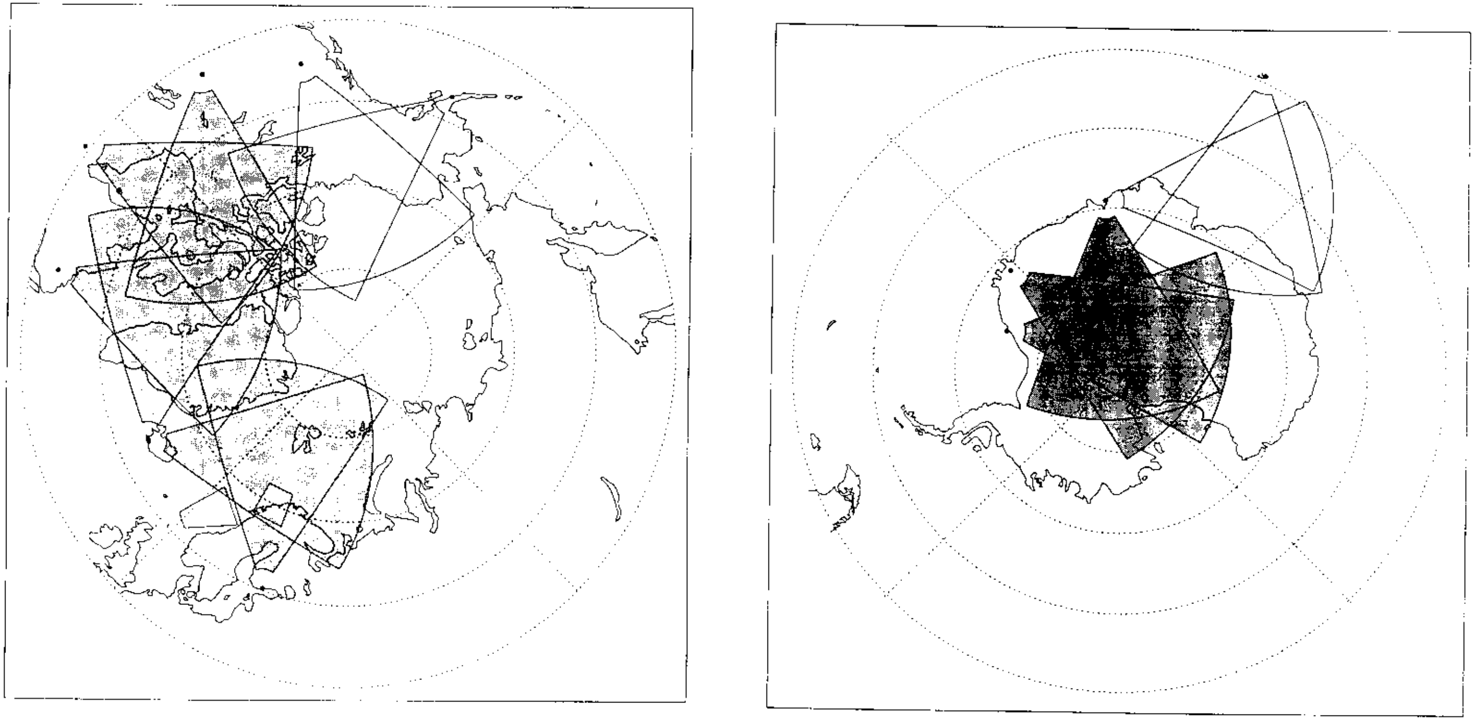

Figure 1. Overview of the operative (shaded) and planned (unshaded) fields-of-view of the SuperDARN network of bistatic HF-radar systems, in the northern and southern polar regions (left and right panel, respectively). In the northern hemisphere even the VHF systems STARE and SABRE will contribute to the SuperDARN coverage (see sketches of their smaller fields-of-view in Scandinavia, left panel; from Greenwald *et al.*, 1995).

cusps or other high latitude regions, a field-aligned pointing direction of the ESR radar, and a north-looking EISCAT VHF dual beam experiment combined with a field-aligned UHF pointing direction (as sketched in Figure 2(a)) will allow us to monitor many ionospheric plasma parameters directly under the Cluster satellite and at the same time monitor the temporal and spatial development of convection flow and particle precipitation in a region between the very high latitude polar cap and the auroral zone, equatorward of the region of key interest. When Cluster crosses field lines connected to the auroral zone above the radars, a field-aligned UHF, vertical VHF, and south-looking ESR beam-swing experiment (as depicted in Figure 2(b)) will allow us to monitor precipitation associated events within the auroral zone, and at the same time monitor the region poleward of the auroral zone (e.g., the open/closed field-line boundary) with the help of the ESR radar. A second antenna on Svalbard, which might become available during the later part of the Cluster mission, would be extremely beneficial for this particular experiment mode, allowing us to exchange the ESR beamswing experiment in Figure 2(b) by a permanent dual-beam southlooking mode (see below for a more detailed discussion of the advantages of such a mode over simple beamswinging experiments). Two antennas on Svalbard would also add interesting possibilities to the Cusp experiment in Figure 2(a)). The EISCAT Scientific Advisory Committee has decided that the combined EISCAT/ESR modes shown in Figure 2 will be the basic modes employed during periods of special interest in relation to the Cluster observations. They have been defined for the first year of coordinated observations and may eventually be upgraded or revised as first experience is gained and evaluated.

In this report we do not wish to review the many capabilities and specialities of all above mentioned instruments, this will instead be done in a source-book for Cluster/Ground-based (CGB) Coordination, which is in press as an ESA Special Publication (SP). Rather we wish to review here in more general sense what kind of studies can be conveyed with combined Cluster and ground-based observations, and what kind of observations we wish to coordinate in order to maximize the scientific outcome of the Cluster mission. Finally we will also describe how the existence of interesting data can be monitored with the help of a ground-based database, containing new indices and general summary data.

As mentioned earlier, ground-based observations of the magnetosphere-ionosphere-thermosphere system are obviously a form of remote sensing. As such they are generally less precise than *in-situ* satellite observations. What therefore do they provide which will enhance the scientific return of the Cluster mission? There are a number of important answers to this question. Firstly, ground-based observatories are spread around the globe and so can be used to simultaneously sense widely-separated regions of the magnetosphere system. Indeed, because the magnetic field lines converge with decreasing altitude, a single ground-based station can monitor a very extensive region of the magnetosphere. However, there are more subtle advantages to ground-based studies. In recent years, the study of transient events and rapid temporal changes in the magnetosphere-ionosphere system has been one

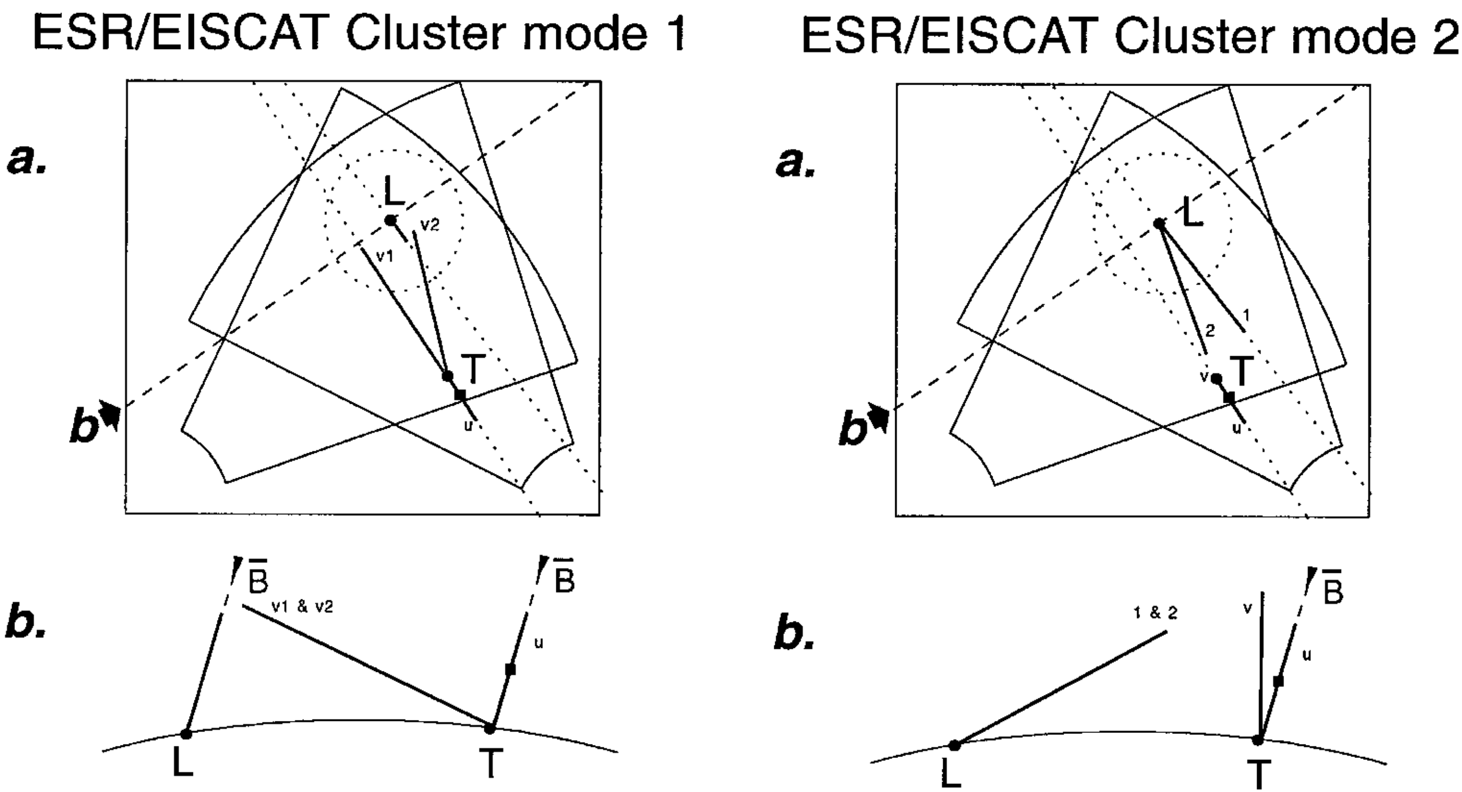

Figure 2a–b. Left: Topview (a) and sideview (b) of the EISCAT and ESR antenna pointing directions proposed for observations in association with Cluster passages through the inner or outer cusp close to Svalbard. In the upper panel (topview) the magnetic meridians through Tromsø and Longyearbyen are indicated by dotted lines. The dotted circle marks the field-of- view of an All-Sky-Camera at Longyearbyen, for 630,0 nm emissions at 250 km altitude. The broken line indicates the viewing direction for the sideview in the bottom panel. We also indicate the combined field-of-view of the European pair of SuperDARN radars, CUTLASS. The filled square marks the altitude, resp. location, of the UHF tristatic electric field measurement. *Right*: as the left but for Cluster observations within the nightside auroral oval and magnetotail regions.

of the most active areas of solar-terrestrial physics research. Ground-based remote-sensing observations have a vital role to play in these studies because they are unique in covering a range of invariant latitudes, at high time resolution and for an extended period of time. *In-situ* satellite observations, on the other hand, provide much higher resolution data but suffer from spatial-temporal ambiguity and from limited spatial coverage. For both remote sensing and *in-situ* measurements, there is a trade-off to be made between spatial coverage, time resolution and the length of the continuous data sequence in any one region of the coupled magnetosphere-ionosphere system. For *in-situ* observations this compromise is set by the orbital dynamics of the satellite; for spatially-integrating ground-based instruments (like magnetometers) it is set by the rotation period of the Earth; but for instruments like radars and imaging riometers, with multiple or steerable beams, this choice can be varied within broad limits set by the rotation of the Earth and the scanning capabilities of the instrument.

Not only are there problems of distinguishing spatial structure from temporal changes in data from a lone spacecraft, but also we cannot determine the motion nor the orientation of observed structures and boundaries. These problems will be addressed in three dimensions for the first time by the four Cluster spacecraft, flying in known but variable configurations. However, they will only answer questions on certain temporal and spatial scales, depending on their separation and altitude (and hence velocity). Ground-based observations can be used in a number of ways to provide important support for Cluster data and greatly enhance the mission's scientific return.

From a survey of the literature Lockwood and Opgenoorth (1995) have defined four classes of scientific investigations, where simultaneous satellite and ground-based observations will be advantageous over single instrument data. We do not attempt to review all such measurements in this paper, but give selected examples to illustrate the classes of application and to look at their particular potential for combined Cluster and ground-based observations.

1.1. Resolution of Spatial and Temporal Variations

The ground-based data can be used to extend the range of time scales of temporal variations which can be studied and can also be used to interpolate between data taken at different times by different Cluster craft at a given point in space. Recent examples of this kind of application (with lone satellites) have included studies of precipitation of magnetosheath-like plasma in what we now know to be transient events, called travelling convection vortices (TCVs), as detected by conjugate arrays of ground-based magnetometers and radars (Potemra *et al.*, 1992; Heikkila *et al.*, 1989). A second example of such an application is the resolution of spatial and temporal variations of the magnetopause reconnection rate (which give cusp ion 'steps' in satellite data) by using simultaneous incoherent scatter observations (Lockwood *et al.*, 1993a; Lockwood, 1995a). A related study by Pinnock *et al.*

(1993) showed that the region of cusp precipitation, as seen by a low-altitude satellite, was co-incident with a longitudinal flow channel seen by an HF backscatter radar: longitudinal flows were also detected by the satellite, but only the radar could resolve that this flow channel was elongated and that it was one of a sequence of transient flow events. Both transient longitudinal flow channels and cusp ion steps are predicted ionospheric signatures of magnetopause reconnection bursts (i.e., flux transfer events or FTEs): the flow channels are expected when the magnitude of the dawn/dusk component of the magnetosheath field is large, the cusp ion steps will be more common when it is small. Such predictions for these, and other, transient events will be ideally tested by combined ground-based observations of the cusp ionosphere while Cluster is at the dayside magnetopause or crossing the dayside auroral oval.

1.2. Placing satellite observations in context

We can also use ground-based observations to place the Cluster observations in context, in both time and space. For example, ground-based data can be used to define boundaries (e.g., convection reversal boundaries, the auroral electrojets, the locations of arcs, the zero potential contour between flow cells), which can give information about which regions of the magnetosphere-ionosphere system the spacecraft were in. Using ground-based instrumentation, sequences of magnetospheric changes can be monitored and certain Cluster observations can be put into the right context of the development stage of the disturbance, as e.g., substorms. It will also be possible to monitor the overall disturbance state of the magnetosphere for individual limited periods of Cluster data.

An example of placing a spatial structure in context of the larger-scale spatial distribution is the recent work on the dayside field-aligned currents and magnetosheath-like plasma precipitations by de la Beaujardère *et al.* (1993). They used radar observations of the convection pattern to resolve an ambiguity of which convection cell a satellite passed through. Likewise, ground-based data can determine when a feature was seen by a satellite in a sequence of events. This is particularly important for studies of the evolution of the magnetosphere-ionosphere system during substorms. Opgenoorth *et al.* (1989) employed ground-based data to investigate the evolution of a westward-travelling surge and showed that the satellite data were within the surge head which had recently ceased moving. Pellinen *et al.* (1992) used ground-based data with auroral images from satellites to show that the recovery phase is much more complex than a simple global return to quiet conditions. Even from multi-satellite data both observations would not have been clearly attributable to the corresponding substorm phases.

Using ground-based data to place satellite measurements in a sequence of events has sometimes produced results which appear to conflict with the conclusions of other studies, which place them in a certain region of the magnetosphere-ionosphere system. There is much to be gained from resolving such conflicting evidence. For example, a major question in recent substorm research has been when and where substorm onset is located and, a related question, when and where the open lobe flux built up in the growth phase is destroyed by tail reconnection. McPherron *et al.* (1993) used ground-based observations of substorm onset to show that tail lobe field strengths begin to decay at onset, implying that enhanced tail reconnection causes onset and that the poleward expansion of the aurora is due to the closure of open flux. On the other hand, Lopez *et al.* (1993) compared particle and field data from the tail plasma sheet with observations by ground magnetometers and auroral imagers and have provided evidence that the tailward expansion of activity in the near-Earth tail is related to the poleward expansion of the aurora, implying that onset is located Earthward of, and occurs before significant closure of open flux by tail reconnection. It is clear that the resolution of these conflicting observations will require combinations of ground-based and satellite data (see review by Lockwood, 1995b). It may eventually help to resolve the general debate between the 'classical near-Earth neutral line' model and the 'Kiruna conjecture', which included a simultaneous or initial disruption of the cross tail current at 8 to 10 R_E in the substorm onset mechanism (see Kennel *et al.*, 1992). The orbit and separation of the Cluster spacecraft will be ideal to study the causal sequence of substorm features in the near Earth magnetotail, as it allows to determine the direction of propagation of various disturbances in the magnetospheric plasma. This may finally resolve the temporal sequence of the processes involved and clarify the location of the initial disturbance onset.

1.3. PROVIDING IONOSPHERIC BOUNDARY CONDITIONS TO STUDIES OF MAGNETOSPHERE-IONOSPHERE COUPLING

The ionosphere is not just a passive mirror of magnetospheric processes, but an active part of a genuinely coupled system. In modelling the magnetospheric observations, it is vital to know the prevailing boundary conditions in the ionosphere. In particular, ionospheric conductivities are of importance and can be derived from altitude profiles from incoherent scatter radars or by comparison of electric and magnetic field values (e.g., Kirkwood *et al.*, 1988; Buchert *et al.*, 1988; Brekke *et al.*, 1989; Kirkwood, 1994). Observed conductivities can be used in a wide variety of ways to add crucial information to a number of studies. These include: studying Alfvén wave reflection at the ionosphere, for example in TCV events (Glassmeier, 1992); testing theories of magnetosphere-ionosphere interaction, for example in substorms (Kan, 1993) and, in particular, using numerical models (Hesse and Birn, 1991a); calculating inductive time-constants for non-steady convection (Sanchez *et al.*, 1991); estimating Ohmic heat dissipation (Foster *et al.*, 1983; Heelis and Coley, 1988; Weiss *et al.*, 1992) and deriving snapshots of the convection pattern by magnetometer inversion techniques (Richmond, 1992; Knipp *et al.*, 1993).

1.4. Quantitative Estimates from Combined Data

Ground-based data can also be used with satellite data to gain information which cannot be obtained from either on their own. Obvious examples of this type of application would include the recognition of structures and sequences of events such that the mapping of convection-dispersed particle populations, waves, magnetic and electric fields from the magnetosphere to the ionosphere is revealed (for example, (Elphic *et al.*, 1990)). However, there are other less obvious applications: Lockwood *et al.* (1993a) have recently used a combination of satellite and radar data to compute the distance from the magnetopause reconnection site to the satellite. This measurement is not possible from either of the two data sets in isolation. Another example is the comparison of electron spectra seen at a satellite with that inferred at low altitudes on the same field line by an IS radar, giving evidence for field-aligned particle acceleration at heights between the two (Kirkwood *et al.*, 1989; Kirkwood and Eliasson, 1990). At low altitudes the consecutive passage of four satellites through virtually one and the same region of space will help to reveal spatial and temporal variations of field-aligned acceleration processes.

2. Conjunctions and Constellations

In order to plan coordinated observations using Cluster and ground-based facilities, the European Space Agency ESA established a working group (Opgenoorth, 1993) for which the authors act as chairman (HJO) and the representative for incoherent scatter facilities (ML). The working group has met several times and organised workshops in Orleans, France, in March 1994, and Rome, Italy, in April 1995. As an initial basis for planning coordinated observations, the working group has followed ESA's Cluster Science Plan by classifying the orbits, such that apogee falls into one of four magnetic local time (MLT) sectors, namely 6 hours around 0, 6, 12, and 18 MLT (i.e. the midnight, dawn, noon and dusk sectors). We also consider the ground-based station or meridian chain of stations to be simultaneously with Cluster in one of the same four MLT sectors, which divides the possibilities into a total of 16 combinations. For each of the 16 there are a number of points on the Cluster orbit near which coordinated observations with a certain ground observatory are of special scientific interest. Thus far, we have defined 67 such conjunctions and configurations. Note that in this paper, we refer to 'configurations' between any one ground-based observatory and the group of four Cluster spacecraft: this should not be confused with the configurations of the four craft, relative to each other, which is variable and an important and complex part of the operations planning for the Cluster mission (Rodriguez-Canabal *et al.*, 1993). The numbers in Figure 3 refer to those configurations or conjunctions which we have identified for periods when the Cluster orbit plane is close to the noon-midnight (GSE XZ) plane, whereas those in Figure 4 are when the orbit plane is closer to the dawn-dusk (GSE YZ) plane.

Figure 3 views the Earth and the Cluster orbit (thick line) from dusk and the small arrow shows the location of a considered key ground-based observatory or local network of stations. The thin lines show a typical magnetopause location, along with geomagnetic field lines which thread the dayside low-latitude boundary layer (LLBL), the high latitude boundary layer (HLBL) or mantle and the tail neutral sheet. Figure 4 views the Earth and the Cluster orbit from the Sun and the thin lines show a typical magnetopause and field lines which pass through the low-latitude boundary layer on the dawn and dusk flanks of the magnetosphere.

To understand what is meant here by a configuration, consider the segment of the orbit marked 1 in the top left part of Figure 3. For this configuration, the satellites are near apogee in the central current sheet of the tail, while the ground-based station in question makes observations of the midnight sector auroral oval. This is an example of a near-conjugate configuration. However, we also consider many non-conjugate configurations to be important. Configuration 2, on the same plot, is one such case, allowing ground-based observations of the development of the substorm aurora and electrojets in the midnight sector while Cluster makes simultaneous observations in the tail lobe. In Figures 3 and 4 we label configurations where the ground-based observatory and Cluster are in opposite hemispheres with an asterix. In many of these cases, much of the same science can be addressed as when the two are in the same hemisphere; however, the interpretation of such data is often likely to be more difficult and, unless there are specific reasons to the contrary, the opposite-hemisphere configurations are considered to be of lower priority. However, we note that in cases where the satellite and radar data can be considered to be of similar type and quality, we may sometimes be able to use opposite-hemisphere observations to test for conjugate and non-conjugate phenomena (e.g., Greenwald *et al.*, 1990; Rodger *et al.*, 1994b).

A comprehensive list of potential scientific objectives for each numbered conjunction or configuration in Figure 3 and 4 is presented in the paper by Lockwood and Opgenoorth (1995) and the reader is referred to that paper or, better still, to an on-line interactive implementation of Figures 3 and 4 which can be acessed via World-Wide Web on Internet, with a graphics-handling browser such as Mosaic or Netscape (the relevant URL is http://www.gbdc.rl.ac.uk/). One of the main purposes of this list is to provoke thought about the potential uses of a ground-based observatory when in a certain configuration with the Cluster spacecraft. Configuration 1, for example, is when Cluster is near apogee and near the tail neutral sheet, while the ground-based observatory is near midnight, configuration 2 has Cluster in the tail lobe (on a pass with apogee near midnight), with the ground-based observatory near midnight. Note that these configurations will not occur in the order 1, 2, 3, ..., for any one observatory because as the satellites move along the orbit, the ground-based station rotates with the Earth. Note also that one configuration for one observatory will simultaneously be a different number configuration for another station. For example, the EISCAT and Söndre Strömfjord incoherent scatter radars are separated by approximately 6 hours of MLT. Thus,

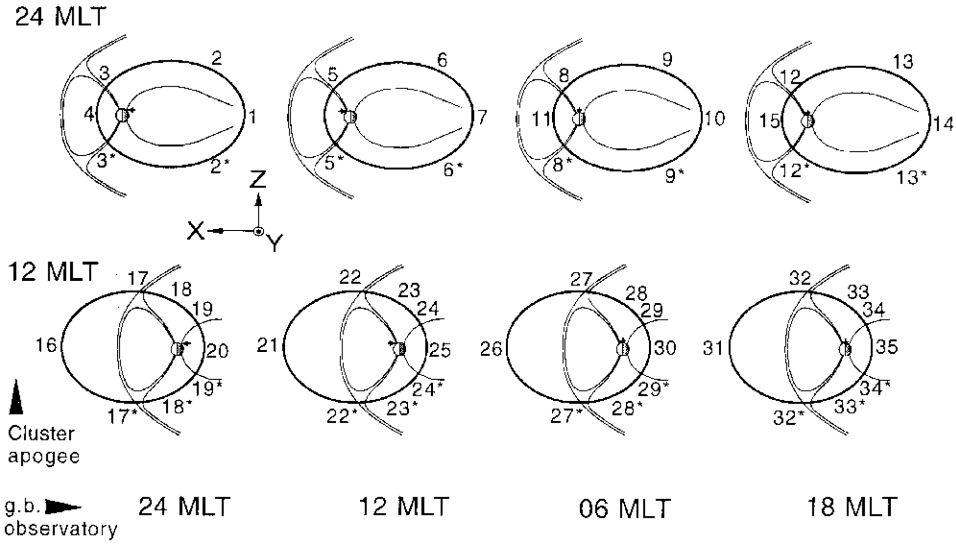

Figure 3. Cluster orbits for when the orbit plane is close to the noon-midnight (GSE XZ) plane. The Earth and the Cluster orbit (thick line) are viewed from dusk and the small arrows show the location of a ground observatory (in this case EISCAT/ESR). The thin lines show a typical magnetopause location along with geomagnetic field lines which thread the dayside low-latitude boundary layer (LLBL), the high latitude boundary layer (HLBL or mantle) and the plasma sheet boundary layer. The numbers refer to satellite locations for configurations/conjunctions with the ground station which we have identified to be of particular scientific interest (see text). The upper row of four figures are all for satellite apogee in the midnight sector and the lower row are for apogee in the noon sector. The vertical columns are for the sector in which the ground-based observatory is situated (i.e., from left to right at midnight, noon, dawn and dusk), when the satellite is at the numbered location. Note that because the ground observatory rotates as the satellite moves along the orbit, the numbered configurations occur in a complex sequence. Configurations where the ground station and Cluster are in opposite hemispheres with an asterix (from Lockwood and Opgenoorth, 1995).

for example configuration 5 (with EISCAT in the noon auroral oval and Cluster flying through the mid-altitude cusp) would simultaneously be a configuration 8 for Söndre Strömfjord, which would then be in the dawn auroral oval. It is important to consider all the possible useful configurations between any one station and Cluster, because the number of ideal configurations for each individual station is limited. Furthermore, the separation of the 4 Cluster craft will be different in one year from when in the same location one year later. This means that particular configurations, which were considered useful during the first year of Cluster observations, will not exactly reoccur during the second year.

3. Examples of Scientific Problems to be Adressed for a Few Direct Conjunctions

The permutations of science topics and satellite-ground configurations identified in the Cluster/Ground-Based (CGB) Online Planning Tool are far too numerous to

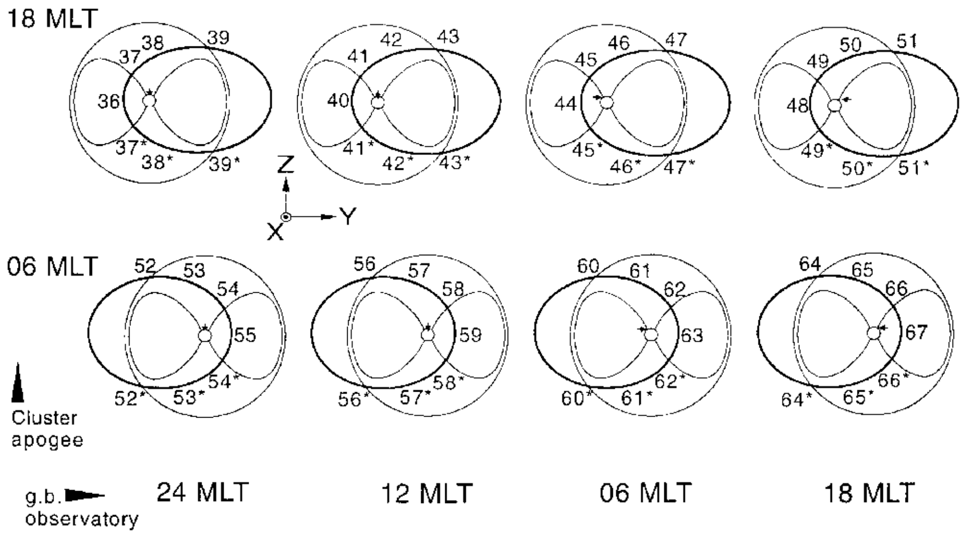

Figure 4. Corresponding plots to Figure 3 for when the orbit plane is close to the dawn-dusk (GSE YZ) plane, so that satellite apogee is in the dusk sector (upper panel) or the dawn sector (lower panel). The Earth and the Cluster orbit (thick line) are viewed from the Sun and the thin lines show a typical magnetopause and field lines which pass through the low-latitude boundary layer on the dawn and dusk flanks of the magnetosphere (from Lockwood and Opgenoorth, 1995).

discuss here in detail. However, to illustrate the choice of scientific objectives and the priorities, we will here shortly illustrate the potential possibilities for mainly two cases, giving outlooks to closely related conjunctions. We chose configuration 1, one of the most important of many novel possibilities for substorm studies, and configuration 5, which will give extremely exciting new possibilities for studies of the dayside boundary layers and cusp. These two cases exemplify the kind of arguments and thinking we have used in the compilation of the topical priority lists displayed in the planning tool at the CGB database.

3.1. Studies of Nightside Magnetospheric Disturbances when both Cluster Apogee and a Concentration of Ground-Based Instruments are Close to Magnetic Midnight (Configuration 1)

Configuration 1, with Cluster in the nightside magnetotail conjugated with a concentrated ground-based network area such as Fenno-Scandinavia, North-America, or Greenland is ideal for studies of the substorm cycle with its many, still unsolved problems.

Even during times of extreme magnetic quiescence, often associated with northward IMF conditions, the magnetosphere does not remain undisturbed. Kamide *et al.* (1975, 1977) and Lui *et al.* (1976) have shown that substorm-like magnetic activity can occur, even on a highly contracted auroral oval. To study such phenomena we require observations of the contracted oval, by stations and radars with a

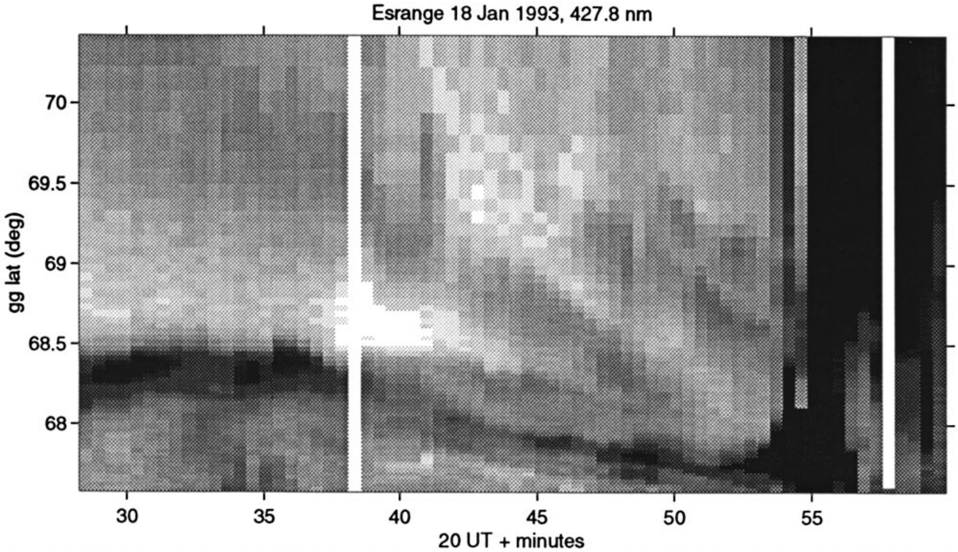

Figure 5. Measurements versus latitude and time of the 427.8 nm auroral emission with a scanning photometer at Esrange, Sweden. The grey scale is logarithmic, with white and black corresponding to intensities below 700 R and above 7000 R, respectively. The two white vertical bars are due to backgrond measurements. Grey structures correspond to southward drifting auroral arcs, and the black structure after 2052 UT to the northward expansion of an auroral break-up (from Persson *et al.*, 1994b).

field-of-view at very high-latitudes, along with simultaneous Cluster measurements in the tail lobe or plasma sheet. Since disturbances during quiet times are by definition localized and small in amplitude, the multi-spacecraft concept of the Cluster mission will improve our chances to (a) observe and (b) identify such events. Other features of the relatively quiet magnetosphere during northward IMF are the so-called ‘Theta’ auroras and Sun-aligned arcs (Murphree and Cogger, 1981; Frank *et al.*, 1982; Murphree *et al.*, 1989) and auroral structures within the polar cap, such as in the ‘teardrop’ or ‘horse-collar’ aurora (Hones *et al.*, 1989). Detailed studies of such very high latitude phenomena will be possible with the new ESR and SuperDARN radars as well as Söndre Strömfjord and EISCAT. Understanding the possible underlying magnetospheric processes and topology will be considerably improved by multisatellite observations in the magnetospheric tail lobes and plasma sheet.

The early development of a substorm is often characterized by equatorward-drifting auroral arcs. They are seen in the late growth phase and early expansion phase, poleward of where onset will later occur, respectively has already occurred. A typical example of such multiple southward drifting arcs prior to the poleward substorm expansion is shown in Figure 5. This data is from a latitudinally scanning photometer and was earlier published by Aikio *et al.* (1996) and Persson *et al.* (1994b). The dark striations in the figure correspond to multiple southward drifting arcs in the substorm growth phase, which starts at about 20:30 UT. The equatorward drift motion of these arcs was observed to be unaffected by a substorm onset at lower latitudes, starting from the equatormost auroral arc close to the isotropic trapping boundary. Only after several minutes the arcs were engulfed by the expanding substorm aurora. This observation supports the concept of substorm onset occurring in the near-Earth central plasma sheet, such that the boundary plasma sheet (BPS) and plasma sheet boundary layer (PSBL) remain unaffected at least for the first ten minutes of the expansion phase after onset (see also Persson *et al.* (1994a, b) and Gazey *et al.*, 1995). With a single satellite it is hard to identify such structures, but they are clearly seen in auroral images and IS radar data and the combination of such ground-based facilities and the four Cluster satellites will be invaluable for the identification of the magnetospheric sources of these arcs and their associated field-aligned current systems (Fukunishi *et al.*, 1993).

The mechanism that leads to the onset of a magnetospheric substorm is still the prime unsolved question of magnetospheric research. Recently, the scenario of the so-called ‘Kiruna Conjecture’ of substorms (Kennel, 1992) has increasingly gained acceptance. This is because evidence has accumulated that substorm onset usually takes place around $X = -8\ R_E$, which is relatively close to the Earth in the central tail current sheet (see Lui, 1991, and references therein). In contrast to such an inferred near-Earth location of onset, signatures of reconnection (specifically the direction of accelerated plasma flows and the polarity of the magnetic field across the tail current sheet) place the near-Earth neutral line (NENL), which is a competing mechanism for the initial substorm onset, somewhere beyond $X = -20\ R_E$ (Baumjohann *et al.*, 1991; Baumjohann, 1993). This conclusion is very important, because it may indicate that the observed disruption of the cross-tail current at substorm onset is not co-located with the NENL but happens considerably Earthward of it. Important questions will then have to be raised as to whether the NENL gives rise to the current disruption, or *vice versa* (see review by Lockwood, 1995b). From recent modelling studies (Hesse and Birn, 1991b) it appears as if the near-Earth neutral line formation would be responsible for the production of vorticity and flux pile-up in the plasmasheet Earthward of it, which could as a secondary effect lead to the formation of a current wedge there.

In a very recent study Nakamura *et al.* (1994) have used data from the IMP 6, 7, and 8 satellites to study the characteristics plasma flow and magnetic field characteristics close to the neutral sheet. They found strong evidence (fast tailward streaming plasma flows, and negative B_z) for near-Earth neutral line formation in association with substorms. Because of the orbital characteristics of the used satellites they could identify the probable region for NENL formation to lie between 18 and 24 R_E, which is closer than earlier studies based on Ampte/IRM would place it (see above).

These recent results are very promising for the Cluster mission. With an apogee at 19.5 R_E Cluster will in configuration 1 have a reasonable chance to pass through the likely region of NENL formation, and should at the same time, according to the Kiruna conjecture, be able to see signatures of the substorm current disruption expanding tailward. It will be of crucial importance for the understanding of the causality of substorm processes to have four-satellite observations in this region at the right moment of substorm development. On the ground the IS and HF radars, surrounding magnetometer arrays, and other ground-based instrumentation such as optical and riometer imagers, will allow us to monitor the onset and spreading of the current disruption, thereby identifying when such Cluster observations are being made. It is crucial to understand when in the evolution of the substorm (as seen from the ground) do the signatures of tail reconnection (as seen by Cluster) commence and how do they relate in time and space to the near-Earth current disruption features. In the later development of the substorm we also need to investigate when the NENL starts to reconnect open lobe flux, thereby detaching the plasmoid from the Earth (Moldwin and Hughes, 1992; Slavin *et al.*, 1992). Note that by the time that this pinching off takes place, the plasmoid may well be already moving down the tail (Owen and Slavin, 1992). Opgenoorth *et al.* (1994) have recently shown that there are clear auroral intensifications even in the later phases of substorm development (in the recovery phase), and these may be associated with the relatively late detachment of a plasmoid. As a characteristic sign of such enhanced recovery phase precipitation they found a strong, possibly purely adiabatic acceleration to energies between 20 and 30 keV. The spatial dynamics of near-Earth recovery of the magnetotail are still completely unknown, but could be studied if Cluster is at the right time at the right place. Again only ground-based data can help to identify those intervals of Cluster data, which would be valuable for a study on this particular topic.

Ground-based data often show a substorm onset, which subsequently fails to develop into a full substorm (Lui *et al.*, 1976; Untiedt *et al.*, 1978; Koskinen, 1992). At other times substorms fail to develop at all over a prolonged perid of time, despite favourable IMF condititons (Yahnin *et al.*, 1994; Sergeev *et al.*, 1994). During multiple substorm intensifications the appearance and strength of the disturbance does not always agree in the ionosphere and the near-Earth space (Yeoman *et al.*, 1994; Grande *et al.*, 1992, 1994). To understand the relative energy release during real substorms, incomplete substorms (pseudo-breakups) or multiple-onset substorms it will be important to detect and track the development of the open/closed field-line boundary with the multiple Cluster spacecraft, and appropriate ground-based instrumentations such as incoherent scatter radars.

3.2. Studies of Dayside Boundary Layers, Cusp and Cleft Using Configuration 5

The previous sub-section considered measurements by Cluster near apogee on the nightside of the Earth. By way of contrast, we here will concentrate on the special aspects of mid-altitude Cluster measurements, on dayside auroral field-lines. Specifically, we look at configuration 5 from Figure 3, to illustrate the

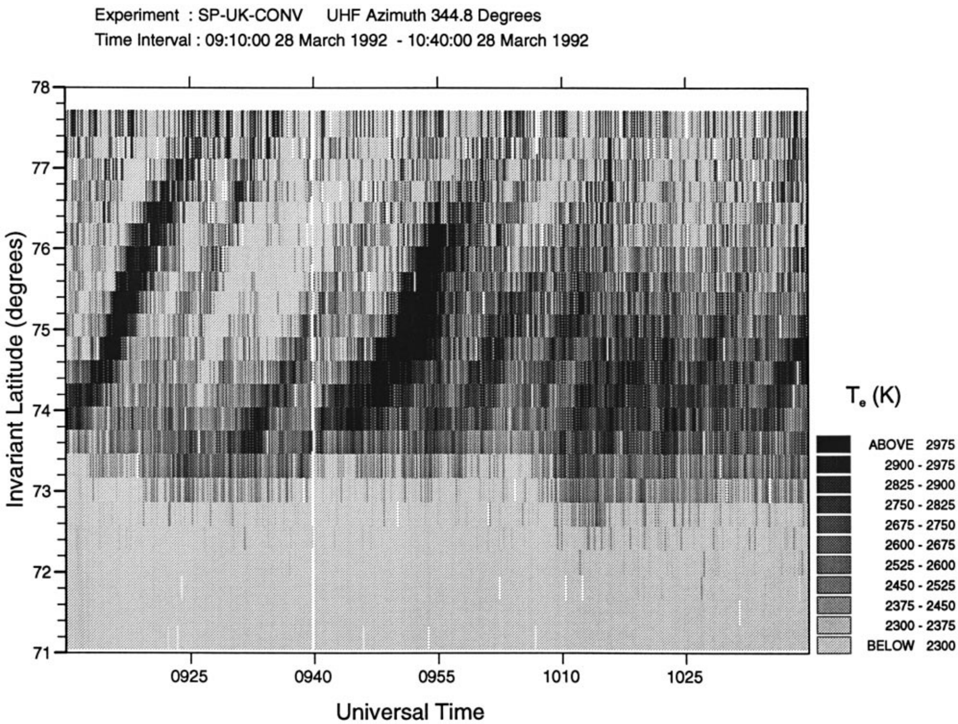

Figure 6. Measurements versus latitude and time of the F-region electron temperature with a north-looking EISCAT UHF experiment at low elevation. Dark structures correspond to northward moving regions of high electron temperature (from Lockwood *et al.*, 1993a).

benefits of the Cluster four-satellite concept, when not in tetrahedron configuration, for coordinated measurements with ground-based instruments. Close to perigee the satellite configuration will be more or less linear along the Cluster orbit (a 'string of pearls'), which means that the satellites will consecutively pass through almost the same regions of space. Depending on the original, near-apogee tetrahedron size, the time span for repetitive sounding of any one region will vary between several to several tens of minutes, which may sometimes allow us to monitor the full temporal development of dayside transient events. Ground-based optical instruments in the dayside cusp/cleft region have revealed at least two classes of transient events. The first are poleward moving events, which either break away from the background cusp/cleft aurora, or may even collectively make up that background (e.g., Sandholt *et al.*, 1985). These are often associated with longitudinal flow channels (Lockwood *et al.*, 1989) and cusp ion steps (Lockwood *et al.*, 1993a). These contrast with the second class of optical events which are associated with travelling convection vortices (TCV's) (Friis-Christensen *et al.*, 1988; Glassmeier *et al.*, 1989). These move longitudinally around the the oval, away from noon and at latitudes just equatorward of the background cusp/cleft (Jacobsen *et al.*, 1991; Heikkila *et al.*, 1989; Potemra *et al.*, 1992; Lühr *et al.*, 1995).

Much recent interest has focused on how and where reconnection takes place at the dayside magnetopause (see reviews by Lockwood, 1995a; Crooker and Toffeletto, 1995). Lockwood and Smith (1994) have recently made predictions of the cusp ion dispersion signatures, as would be seen by the Cluster craft during mid-altitude cusp crossings, when the rate of reconnection at the dayside magnetopause is pulsed. The predicted poleward migration of the cusp ion steps (caused by the periods of low reconnection rate between pulses) could be detected by comparing the ion data from the different Cluster spacecraft. The theory predicts this motion to be associated with poleward-moving ionospheric electron temperature enhancements, 630 nm (red-line) auroral transients and transient bursts of longitudinal flow. These have already been detected by EISCAT and optical instruments on Svalbard (Lockwood *et al.*, 1993a; Sandholt *et al.*, 1990). Figure 7 shows examples of poleward-moving events seen by the EISCAT UHF radar, as reported by Lockwood *et al.* (1993a). The plot shows electron temperature enhancements in the F-region, consistent with the effects of soft, magnetosheath-like electron precipitation.

Figure 7 is an example of a common form of data presentatiom for incoherent scatter radars, showing a measured parameter (in this case the electron temperature) as a function of time (x axis) and range from the radar (y axis). The plot reveals that the enhancements were propagating away from the radar. This demonstrates the kind of ambiguity that can arise in such radar data, because a fixed beam was used which slants at low elevations through the ionosphere. Thus the observed features could have resulted either from poleward-moving latitudinal structures, or from rising thin altitudinal structures (layers). Fortunately, data were also simultaneously recorded by the VHF radar, pointing at a different elevation and these showed the events were indeed poleward-moving latitudinal structures. Gaining this information could have been achieved with a single radar, but only by scanning the beam and consequently reducing the time resolution to twice the duration of each scan cycle (the Nyqvist limit). Depending on the scan speed of the radar, this could well have caused a failure to detect the poleward-moving events. The data shown are continuous measurements at 10-s resolution, but an analysis of the effects of antenna scanning have shown that the region of enhanced temperatures would have appeared continuous if a scan were used, even if the cycle time was a short as 4 min. The example serves to illustrate how carefully an experiment must be designed if a certain feature (in this case the poleward-moving events) is to be detected. In addition, it illustrates the importance of information on, and understanding of, the radar mode when looking at such data presentations.

The data shown in Figure 7 are very similar in form to keograms of optical emissions from the cusp region, which also show such poleward-moving events when the IMF is southward. Indeed, there are good theoretical reasons to expect the electron temperature enhancements to be associated with red-line (630 nm)

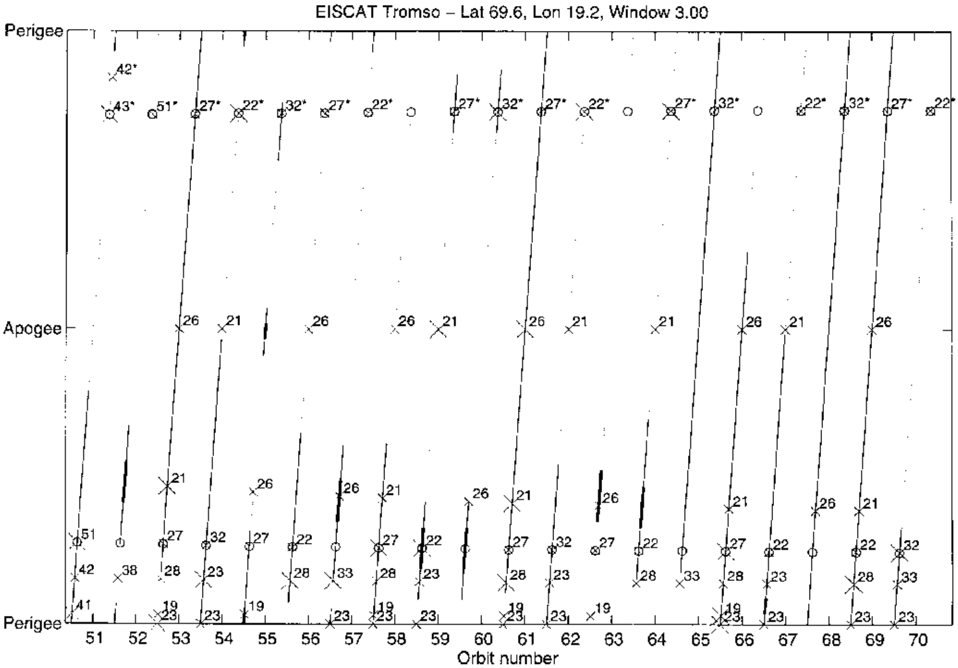

Figure 7. Example of a so called ‘Bryant-Plot’ used for identification of coinciding Cluster and ground-based measurements. Such plots, indicating the periods of Cluster data taking along a sequence of orbits and the times and types of conjunctions with a user selected ground-based instrument, can be created with a WWW tool at the GBDC. The full lines indicate Normal Mode Cluster data taking, the heavier lines Burst Mode periods. The crosses indicate conjunctions or configurations (according to the numbers given in Figures 3 and 4) with the chosen station, and the size of the crosses roughly indicates the quality of the conjunction (see text for more details).

dominant emissions. A key question about the red-line auroral light is the altitude profile of the emissions, as this influences our estimates of the size of the events, as derived from all-sky images (Lockwood *et al.*, 1993b). The emission profiles of 630 nm light are determined by the altitude profiles of ionospheric electron density and temperature, both of which are enhanced by the precipitating magnetosheath plasma in the cusp region. In addition, the transient patches of 630 nm emission are associated with small regions of dominant 557.7 nm (green-line) emission. These were shown, in one case at least, to be coincident with the upward field-aligned current of the oppositely directed matched pair which transmit the longitudinal motion into the ionosphere (Sandholt *et al.*, 1990; Lockwood *et al.*, 1993b). However, the causes of the required electron acceleration are not known. The new ESR IS radar will be ideal for studying these processes and the emission profiles because Svalbard offers optical observations of the cusp in darkness, as well as field-aligned radar measurements of ionospheric parameters. In particular, if reconnection pulses are confirmed to be the origin of poleward-moving events in the radar data, it becomes crucial to measure their area because this gives an estimate of the total flux opened by each reconnection pulse, and hence the contribution to the average transpolar voltage (see Lockwood *et al.*, 1993b).

Thus the combination of the EISCAT, ESR and Cutlass radars with optical observations will be and ideal complement for Cluster electron and ion precipitation observations for configuration 5. From these combined observations we should be able to determine where the reconnection takes place, how the reconnection rate varies and what conditions prevail at the reconnection site (see Lockwood, 1995b; Lockwood *et al.*, 1994).

However, a major complication in this area of research has been that transient flows, aurorae and field-aligned currents are also key features of travelling convection vortices (TCV's) (Friis-Christensen *et al.*, 1988; Glassmeier *et al.*, 1989). These are thought to result from solar wind pressure pulses but a variety of different mechanisms have been proposed (Kivelson and Southwood, 1991; Lysak and Lee, 1992). Thus the origin, as well as the propagation and lifetime, of TCVs is still not known. In addition, they appear to be associated with soft precipitation equatorward of the background cusp/cleft (Heikkila *et al.* 1989; Potemra *et al.*, 1992; Jacobsen *et al.*, 1991; Lühr *et al.*, 1995) which is not predicted by the current theories of their generation. For these studies it might be beneficial to have configurations between Cluster and ground-based radars which are not exactly conjugated, but rather offset by some longitudinal difference of $\leq 90°$ (see, e.g., configurations 8, 12, 27, 32 in Figure 3). In these configurations Cluster might monitor the TCV formation process while ground-based stations could follow the drift along the late morning or early afternoon auroral oval. The large scale magnetometer networks and semiglobal coverage of the SuperDARN radars will add important additional information.

As on the nightside, magnetic mapping is uncertain in the cusp/cleft region, and in addition is likely to be highly dependent on the amount of open flux threading the dayside magnetopause (Crooker et al., 1991; Crooker and Tofelletto, 1995). Induction effects mean that the voltage pulses (i.e., flux transfer events) in the magnetopause are decoupled from the ionosphere where they may cause only smoothed poleward flow unless the magnetosheath B_y component is large [see review by Lockwood, 1995a). Comparisons between radar flow observations and Cluster data, when in close conjunction in the cusp/cleft region will help answer the vexed questions of how both magnetopause magnetic and electric fields map into the ionosphere. Much attention has been given to the cusp when the IMF is southward and relatively little to its behaviour when it is northward, which can often be complex (e.g., Weiss *et al.*, 1995). Configuration 5 would be valuable for studying how the northward IMF cusp relates to transpolar arcs and sunward convection in the lobe.

Lastly, the cusp/cleft region is known to be a major source of ionospheric plasma for the polar magnetosphere in the cleft ion fountain (Lockwood *et al.*, 1985). The IS radars and digital ionosondes could be used to detect the upflows in the cusp ionosphere while the Cluster spacecraft observe them in the dayside auroral oval and their dispersion by convection into the near-Earth lobe. Thus the combined Cluster-ground-based data can yield information about the location and causes of the cleft ion fountain.

4. An Operations Scenario

At the time of writing, the exact Cluster orbit is unknown and hence also the UT at which the spacecraft are in any one location. As it is this UT which determines the location of a ground-based facility, this information is vital for planning coordinated measurements with any one ground-based observatory. Consequently, detailed plans on when favourable configurations or conjunctions will occur cannot yet be made. However, to gain an idea for the likely operating schedules we here consider the nominal Cluster orbit of 57 hours (i.e., 2 days 9 hours). Table I illustrates the evolution of the relative locations of the satellites and one ground-based station, as e.g., incoherent scatter radars or other campaign instruments, following an ideal occurrence of just one configuration (the example chosen here is configuration number 5). This conjunction is said to be ideal if the satellites are at noon when crossing the dayside auroral oval, and the considered ground-based observatory is also at magnetic noon (which is at a UT of roughly 9 hr at, e.g., Svalbard). This can be seen to be the case for orbit 1 because the difference in longitude between the ideal and actual radar sites, δL, is zero; as is the difference between the ideal and actual MLT of the satellite, δMLT. At the same point of the next orbit (2), the radar location is far from ideal, with $\delta L = 9$ hr. For orbit 3, δL is -6 hr when Cluster is in the interior cusp. Note that although this is not a usable occurrence of the very important configuration 5, satellite data on the cusp could still be of use for ground-based coordinaton, because it is an ideal occurrence of configuration 8 (which as mentioned above could be used for TCV studies). Orbit 5 gives a configuration 3 when Cluster is in the interior cusp, and would allow for studies of dayside trigger of nightside disturbances. The interior cusp crossing on orbit 7 yields configuration 12, which is of smilar use as configuration 8, but for TCVs drifting along the dusk oval. Configuration 5 is regained on orbit 9. Note, however, that in this 8-orbit cycle, the satellite has drifted by 1.25 hrs of MLT (because the satellite orbit plane moves through 0.156 hours of MLT per orbit, covering 24 hours in a year), and therefore the ideal conjunction of Orbit 1 does not exactly re-occur. If, for example, we wish the satellite to be within 2 hours of the ideal conjunction for any one configuration, we will only have 2 or 3 such configuration re-occurrences per year of the mission. This is true for the nominal orbit, however, any deviation from the planned orbit can alter these numbers in either direction.

A corresponding analysis can be applied to each of the many useful configurations or conjunctions which occur at other portions of the Cluster orbit. The key point for operations planning is that different ideal configurations will occur during the same orbits. For example, the (very high priority) configuration 1, for

Table I
The repetition of a configuration for an orbit period of 57 hours

Oribt number	Day number	UT (hr)	MLT difference of GB station from satellite δL (hr)	Deviation of satellite ML from ideal, δMLT (hr)
1	1	9	0	0
2	3	18	9	0.156
3	6	3	−6	0.312
4	8	12	3	0.468
5	10	21	12	0.642
6	13	6	−3	0.780
7	15	15	6	0.936
8	18	0	−9	1.092
9	20	9	0	1.248

e.g., EISCAT, requires Tromsø at 24 MLT, so that the satellites are at apogee in the tail at about 19:30-23:30 UT. This is roughly achieved during orbit 2 in Table I on day 4 at 23:30 UT and during orbit 7 on day 16 at 20:30 UT. However, other important configurations with other ground-based instruments will also occur in the same period. We have also noticed that often two areas equipped with key ground-based instruments (as e.g., Greenland and Scandinavia) are offset in local time by about 90°, which means that when one local network encounters configuration 1 or 5 the other will encounter configuration 8 or 12 (see Figure 3). Naturally such conjunctions require coordinated operations of the US and European incoherent radars. The complexity of the planning is yet further increased by the choices for operations made by the Cluster SWT, their selection of data-gathering periods, satellite separation strategy and the instrument modes.

This planning cycle may sound extremely complicated, but is actually more easily understandable when presented on an interactive computer system. Therefore we have prepared the so-called Cluster/Ground-Based conjunction planning tool at our data center at the Rutherford Appleton Laboratory (RAL). We make this system available for the STP community on the World-Wide-Web, via Internet. It allows the user to compile a list of the predicted occurrences of one or more of the configurations for a user-specified ground-based observatory, to within a δL tolerance which is also set by the user.

For planning of combined observations, it is vital to know in advance which of the configurations of the satellites with the ground stations will take place during proposed data taking periods. In order to let scientists (using instruments both on Cluster and the ground) see the implications of a proposed data-gathering sequence, the WWW planning tool at RAL provides so-called ‘Bryant Plots’ of the orbit. These were used to great effect during the AMPTE mission and an example for the nominal Cluster orbit is here presented in Figure 7. The plot shows time elapsed since the last occurrence of satellite perigee (y axis) as a function of time (x axis). Each orbit thus appears as a straight line (of unity slope) from on perigee to the next, perigee being at both the bottom and the top of the plot. The number of each orbit is labelled along the x axis at the time when the satellite moves through apogee (at the centre of the x axis). Figure 7 is for a period when Cluster apogee is near noon and in the upstream solar wind. At any one time, one of three line types is used to show the orbit: the thick solid line segments show periods when it is currently planned that Cluster will be taking data in burst mode, the thin line segments are where it is to be in normal mode and the dashed line shows where no data-taking is planned. Also on each orbit we mark the occurrences of certain events, based on statistical magnetosphere models: e.g., in this example magnetopause crossings are denoted by open circles. Figure 7 is based on the version of the Cluster Science Plan of March 4, 1996, using data on the orbit and the data taking plans supplied to the CGBDC at RAL by the Cluster JSOC (Joint Operations Science Centre). The planning tool will always give predictions based on the most up-to-date data from JSOC who will provide such data weekly.

Figure 7 also marks a series of points for each orbit, at which a desirable configuration/conjunction with a user-selectable ground-based observatory takes place. The plot shown in Figure 7 is for the EISCAT site at Tromsø but could be for any site, selected by name or coordinates by the WWW user. Beside each cross, the configuration/conjunction number (as given in Figures 3 and 4) is given. Note that in this period there are several occurrences of configuration 22 (Cluster at the magnetic cusp on the magnetopause, with EISCAT at noon) and configuration 19 (Cluster crossing the nightside auroral oval near perigee while EISCAT is close to conjugate with it). If the configuration/conjunction is a ‘good’ one, the cross is larger in size: ‘good’ defined as the ground station being 1 hour off an ideal location (e.g., for configuration 22, this means the ground station is in the MLT range of 11–13 hr) or the satellite MLT is the same as that of the satellites to within 1 hour. The figure can be used to study the implications of the proposed data taking for the ground-station in question. The planning tool can then be used to get further information of any case in tabular form. For example, data are taken during all of the occurrences of configuration 22 during the 20 orbits shown, with burst mode on orbits 72 and 85, both of which are ‘good’ occurrences. On the other hand, of the 7 occurrences of configuration 19, data are only taken on 3, with only 1 in burst mode. Only on orbit 79 the configuration 19 is classed as ‘good’.

It can also be seen that on orbit 77 burst mode data are taken when the satellites pass through the nightside auroral zone, but this occurs at a time when EISCAT or other ground-based networks are not anywhere close to configuration 19. This is a typical example where the ground-based community (particularly those scientists interested in using EISCAT to study substorms and the nightside auroral oval) could ask for the Cluster burst mode data taking to be moved to, for example, orbit 79 when a good configuration 19 occurs with EISCAT. However such requests of change in the Cluster master science plan will only be requested when the final Cluster orbit is known, and they will have to be related to a whole combination of other change requests for the benefit of other ground-based instrumentation, or general satellite requirements. It will be necessary for the working group to make clear priority choices for change requests.

A Bryant plot of each individual orbit can be obtained from the WWW planning tool, from the lists of configuration(s) selected by he user. For longer-term planning, the user can select the range of orbits required on each plot (Figure 7 shows 20) when he selects the ground-based observatory. It is expected that this planing tool will remain of great use even after the data have been acquired and are being exploited. It will then be used to define periods when data were taken with the satellites and a ground station in a given configuration.

With the help of an image handling browser such as Mosaic or Netscape the planning procedure is easily explorable under the URL **http://www.gbdc.rl.ac.uk/** at the World Data Center C1 at RAL (see also Lockwood and Opgenoorth (1995) for more information on the WWW planning tool.)

5. Ground-Based Summary and Index Data

In order to carry out truely coordinated studies between Cluster and the many ground-based instruments, it will not only be necessary to predict ideal conjunctions and coordinate the actual operation of the measurement. When selecting data from the huge database that is going to be produced, we need also fast and easily accessible criteria to judge, whether the magnetosphere was in an interesting or suitable disturbance state, or whether certain events did or did not take place. To that end the ground-based community will provide the users of Cluster data with a database containing quicklock or summary data from the various instruments and networks. Every instrument type has its own procedure of presenting key observations in quicklook form, and the exact layout of the data will be described in detail in an ESA Special Publication on Cluster Ground-Based Coordination. Here we only show a few examples of how such daily overview plots of certain key instruments can look like. Figure 5, which was discussed above in a more scientific context, is a typical example of a latitude versus time plot, derived from optical instruments such as photometers and All-Sky cameras (ASC). Such plots allow the determination of location and dynamics of precipitation regions in various key areas of the polar regions; dense instrument networks of optical stations do exist in Scandinavia, Greenland, Canada, Alaska, and Antarctica. Similar latitude versus time plots of electrojet positions and strength can be derived from data of magnetometer chains, as they exist e.g., in Canada, Scandinavia and Greenland. No example plots of such data are given here, but the interested reader can find many nice examples on the WWW home pages of the Canopus and Image magnetometer networks. The CGB WWW-pages at RAL will contain direct links to these overview data.

In addition all individual radars of the SuperDARN network will provide daily overviews in the form of range versus time diagrams of backscatter power, line of sight velocity and spectral widths, from the central beam direction. Again, the combined overviews from all radars cannot only inform about the existence and quality of data, but also at the same time provide an initial indication about the spatial and temporal development of ionospheric convection boundaries. A typical example of such a plot from the Finnish SuperDARN station in Hankasalmi (the eastern part of the European CUTLASS system) is given in Figure 8.

Finally, the incoherent scatter radars such as EISCAT, Söndre Strömfjord and Millstone Hill will provide (whenever operative) overview data of the temporal development of certain ionospheric parameters such as electron density, electron and ion temperature and plasma velocity versus altitude or latitude (or both, in case of antenna scans). Figures 9(a) and 9(b) gives a typical example of how the EISCAT multi radarsystem can provide combined information of plasma parameters versus altitude and time, along a field-aligned position as depicted in Figure 2, and at the same monitor the plasma conditions versus range (latitude) and time inside the polar cap for an oblique viewing direction of another antenna (see even Section 3.2 for a more detailed discussion of such type of data). This simultaneous dataset can provide information on both the local precipitation and the expansion and contraction of boundaries and auroral features over an adjacent area further north. As explained above the future combined EISCAT ESR facility, will cover a wide range of the high latitude region with such information.

In many cases the CGBDC is organised in such a way that the actual data for the overview plots will not reside at the CGBDC at RAL, but the users will instead be provided with links to the homepages of the original instrumentations. Apart from the above described optical stations, ionosondes, riometers, incoherent and coherent radars, and of course, magnetometers around the world from both hemispheres, even geostationary satellite data overviews will be available in a similar manner.

To help browsing such key instrumentation another WWW facility at the CGBDC at RAL provides an (as complete as possible) list of ground-based instruments from which data is (or may become) available for coordinated Cluster studies. Only instruments relevant to magnetosphere-ionosphere studies have been included. At present the list contains 850 instruments at over 450 sites. We would welcome any corrections and additions to this list which can be returned to us using the WWW facility We plan to constantly update his list during the Cluster mission. Table II gives the first entries in an alphabetical listing of the instruments as an example for the information contained. The list does not give magnetic coordinates because these are available on the Web pages, using a coordinate system and magnetic field model of the user's choice. This will enable users to obtain all magnetic coordinates in a common and self- consistent frame. The facility will also allow the user to

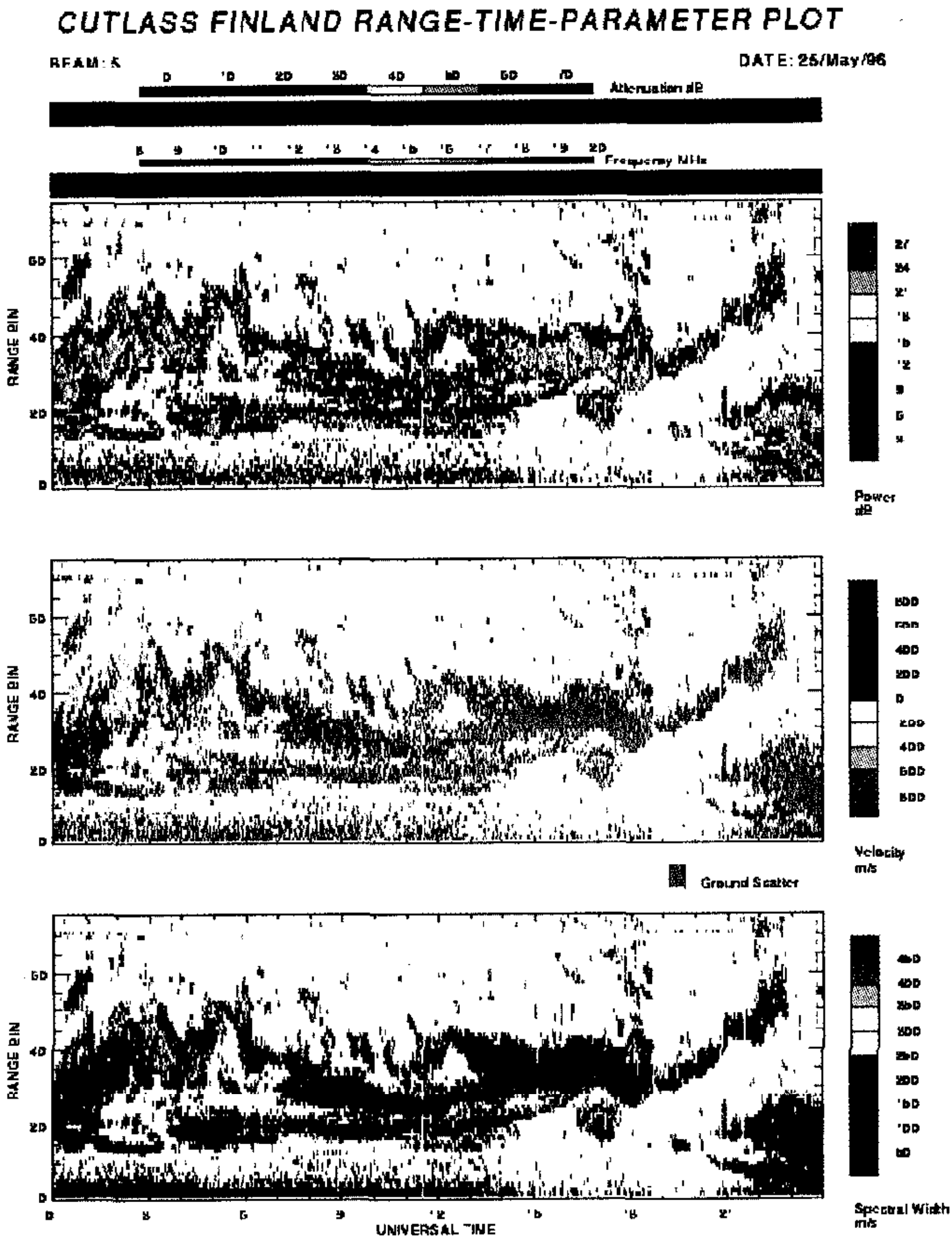

Figure 8. Example of a daily overview plot from an individual SuperDARN radar station, giving a summary of range versus time observations of backscatter power (*top panel*), line-of-sight velocity (*central panel*) and spectral width (*bottom panel*). This dataexample comes from the western station (Hankasalmi) of the European radar pair (CUTLASS), overlooking Svalbard.

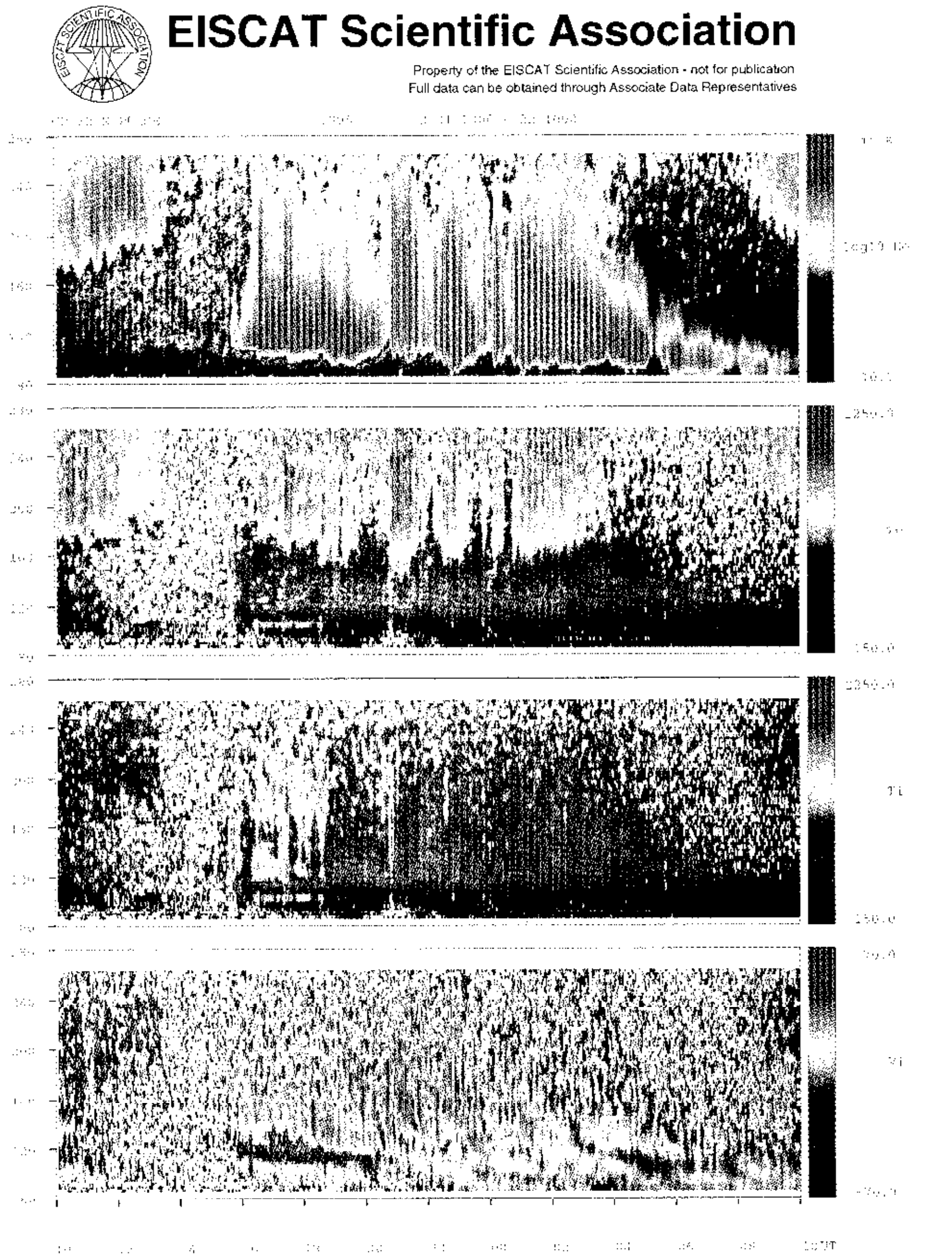

Figure 9a. Daily overview plot of EISCAT measurements of plasmaparameters (electron density, electron and ion temperature and ion velocity) as a function of altitude and time for a field-aligned pointing experiment. Times of precipitation can easily be recognized in the electron density data. (Reproduced with special permission of the EISCAT Scientific Association.)

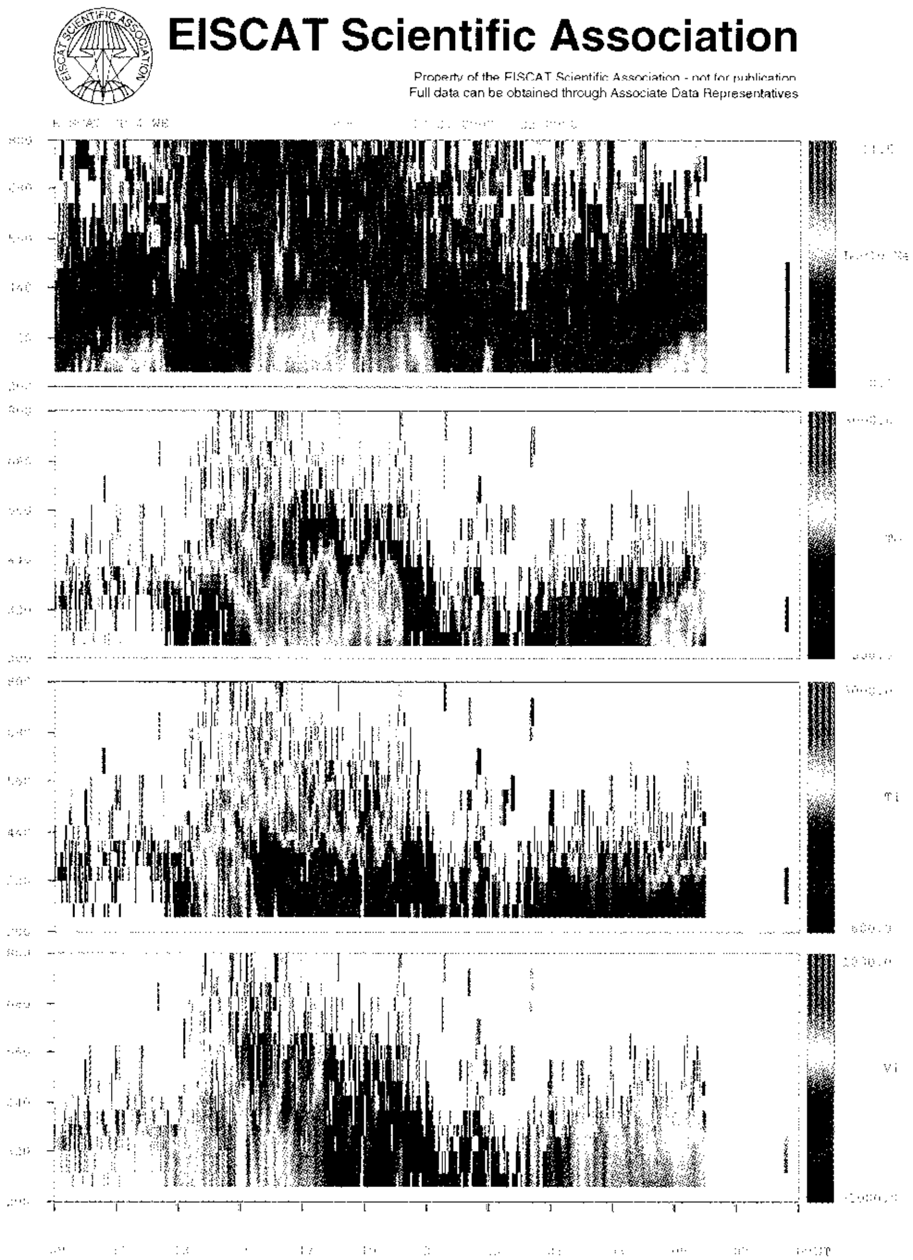

Figure 9b. Daily overview plot of simultaneous EISCAT measurements of plasma parameters (electron density, electron and ion temperature and ion velocity) as a function of range (latitude) and time for an experiment with a north-pointing antenna. In these kinds of plots the expansion of precipitation regions can be identified as regions of enhanced electron temperature. Regions of enhanced ion temperature indicate strong electric fields. (Reproduced with special permission of the EISCAT Scientific Association.)

Table II

Complete list of ground-based observing stations

This is a preliminary list of all ground–based observing stations that we know about. In due course you will be able to select the information from this list using various criteria. Until then, each line in the station list corresponds to one instrument, and thus sites equipped with many instruments appear on several lines. An individual instrument may also appear more than once if it belongs to more than one group of instruments. The entries are arranged alphabetically by station name, and the various codes and acronyms in the list are explained in associated tables:

- Instrument codes (R for riometer, M for magnetometer, ... etc)
- Group acronyms used for chains and networks of stations, for data centres and for instruments.
- Station synonyms where a station is known by more than one name.
- Institution acronyms and abbreviations used to describe the institutes which operate the instrument in question.

The last column of the list is the e–mail address of a useful contact person for the station.

Station	Code	Geographic coordinates	Instr-ument	Chain	Operated by	Contact e-mail
AGO A77	B1	77.58 S 336.63 E	M	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A77	B1	77.58 S 336.63 E	R	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A80	B2	80.75 S 339.60 E	LF-HF	AGONET	U.Stan	jameslabelle@dartmouth.edu
AGO A80	B2	80.75 S 339.60 E	M	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A80	B2	80.75 S 339.60 E	MP	AGONET	ACM	engebret@augsburg.edu
AGO A80	B2	80.75 S 339.60 E	R	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A80	B2	80.75 S 339.60 E	VLF	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A81	B3	81.50 S 3.00 E	LF-HF	AGONET	U.Stan	jameslabelle@dartmouth.edu
AGO A81	B3	81.50 S 3.00 E	M	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A81	B3	81.50 S 3.00 E	MP	AGONET	ACM	engebret@augsburg.edu
AGO A81	B3	81.50 S 3.00 E	R	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A81	B3	81.50 S 3.00 E	VLF	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A84	B4	84.0 S 335.0 E	LF-HF	AGONET	U.Stan	jameslabelle@dartmouth.edu
AGO A84	B4	84.0 S 335.0 E	M	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A84	B4	84.0 S 335.0 E	MP	AGONET	ACM	engebret@augsburg.edu
AGO A84	B4	84.0 S 335.0 E	R	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO A84	B4	84.0 S 335.0 E	VLF	AGONET	BAS	J.Dudeney@bas.ac.uk
AGO I1	I1	74.07 S 164.12 E	M	AGONET	–	–
AGO J1	J1	70.0 S 39.5 E	M(p)	AGONET	NIPR	–
Abisko	ABK	68.35 N 18.82 E	ASC(4freq)	ALIS	IRFK	steen@irf.se
Abisko	ABK	68.35 N 18.82 E	R	-	SGO	Hilkka.Ranta@csc.fi
Abisko	ABK	68.36 N 18.82 E	M	–	–	–
Adelaide	ADL	34.67 S 138.65 E	M	-		.
Adelaide	-	34.7 S 138.6 E	ID	ULCAR	–	reinisch@cae.uml.edu
Agua Verde	-	25.4 S 290.0 E	ID(p,c)	ULCAR	–	reinisch@cae.uml.edu
Aire Sur L'Adour	-	43.4 N 0.0 W	BLS	-	–	–
Akita	AK 539	39.70 N 140.10 E	I	WDC-C1	-	M.Wild@rl.ac.uk
Alert	ALE	82.45 N 297.7 E	ID	-	UWO	macdougal@uwo.ca
Alert	ALE	82.50 N 297.50 E	M	-	GSC	vanbeek@geolab.emr.ca
Alfred Faure	-	46.43 S 51.97 E	M	-	ULP	schlich@??
Alibag	ABG	18.64 N 72.97 E	M	Intermagnet	-	d.kerridge@bgs.ac.uk
Alice Springs	ASP	23.77 S 133.88 E	M	NGDC	BMR	stewart@lodestone.bmr.gov.au
Alice Springs	-	24.0 S 143. E	ID	ULCAR	DSTO	wardbd@hfrd.srl.dsto.gov.au
Alma Ata	AA 343	43.20 N 77.00 E	I	WDC-C1	–	M.Wild@rl.ac.uk
Alma Ata	AAA	43.25 N 76.92 E	M	–	–	–
Almeria	ALM	36.85 N 357.54 E	M	–	–	-
Amderma	AM 269	69.46 N 61.41 E	I	WDC C1		M.Wild@rl.ac.uk
Amderma	AMD	69.40 N 60.20 E	M	–	AARI	olegtro@geophys.spb.su
Amderma (Calgary)	AMD	69.47 N 61.42 E	M	–	–	–
Ammassalik	AMK	65.60 N 322.37 E	M	GreenlandE	DMI/U.Mich	efc@dmi.min.dk
Anchorage	AMU	61.24 N 210.13 E	M	–	U.Alaska	jvo@maxwell.gi.alaska.edu
Andøya	–	69.295N 16.030E	ASC	-	ARR	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	ATV	-	ARR	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	ELF	-	ARR	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	ID(p)	-	IAP Kuehlungsborn	??
Andøya	–	69.295N 16.030E	M	-	ARR	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	MF(p)	·	IAP Kuehlungsborn	??
Andøya	-	69.295N 16.030E	MP	–	ARR	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	MSP	-	ARR	kolbjorn@arr.nsc.no
Andøya	-	69.295N 16.030E	R	–	ARR/DMI	kolbjorn@arr.nsc.no
Andøya	–	69.295N 16.030E	RR	–	ARR	kolbjorn@arr.nsc.no
Andøya		69.295N 16.030E	SIR	–	UWO	??
Andøya	–	69.295N 16.030E	SM	–	MPI Lindau	??
Andøya	–	69.295N 16.030E	VLF	–	ARR	kolbjorn@arr.nsc.no

generate maps of selected stations and to select stations from maps. How to make full use of the planning tool is described within the system itself, and it would be beyond the scope of this article to go into more detail.

While quicklook data often is, strictly speaking, only usable for event selection or classification, one set of ground-based quicklook data has during a long time enjoyed very frequent use in publications and is considered as a direct monitor of the magnetospheric state of energy input or release. These are the magnetic AE indices (Davis and Sugiura, 1966), which represent the maximum horizontal magnetic deflection along a ring of selected magnetometers around the northern hemisphere auroral oval. Useful (and much used) as they are, the AE indices nevertheless have several shortcomings for Cluster and ground-based operations planning, of which the most critical one is relatively slow availibility.

Acknowledging the success and long-term usability of the AE(12) indices we decided to provide a similar index, using data with one minute time resolution from 10 magnetometer stations along the standard auroral oval. The used stations are roughly the same (or at equivalent locations) as the original AE stations. The rationale for deviations from the standard AE procedure was the need for fast and easy data access. A survey of the literature revealed that substorms were usually identified by AE perturbations dominated by large negative AL-values, or simply using the AL-index alone. It was therefore decided that for Cluster mission-oriented tasks AL-type (lower envelope of the magnetic H-disturbance) of indices were required.

Since the basic index is derived from stations along the standard auroral oval, it has been named Standard Oval (SO) index. One of the basic differences in the production of the SO-index is that it will be made available on-line, as soon as data from a few stations have come into the database at RAL. The dataset will then automatically be updated as more data are received. The index will always be quoted with the number of contributing stations in parentheses and in addition, the summary plots will show explicitly the longitude of the stations used. This means that immediate event recognition and selection can be carried out for many coordinated studies within certain key regions of the auroral zone, even if not all data have yet been collected; collaborative studies can be started without delay. Later, while the scientific work is proceeding, the magnetic index will be automatically updated to improve coverage and quality. The user will always be supplied with the most up-to-date index values.

This procedure is a considerable improvement of the accessibility of magnetic indices. There is no immediate drawback in the quality, unless one wants to carry out a study over a region from where data has yet to be received. Recently Kauristie *et al.* (1996) have shown, that local magnetic indices contain much of the information of the full AE(12) index for stations within several hours around magnetic midnight. As a result, many event studies involving ground-based networks in highly instrumented regions need not be delayed by incomplete AE index coverage.

Thus the new index will overcome the problems of timely availability, that the AE index suffers from. The other main shortcoming of the standard AE(12) index is its restriction to stations along the location of the standard nightside oval. During very quiet and very disturbed conditions AE(12) is known not to represent the actual disturbance state of the magnetosphere, but to underestimate it

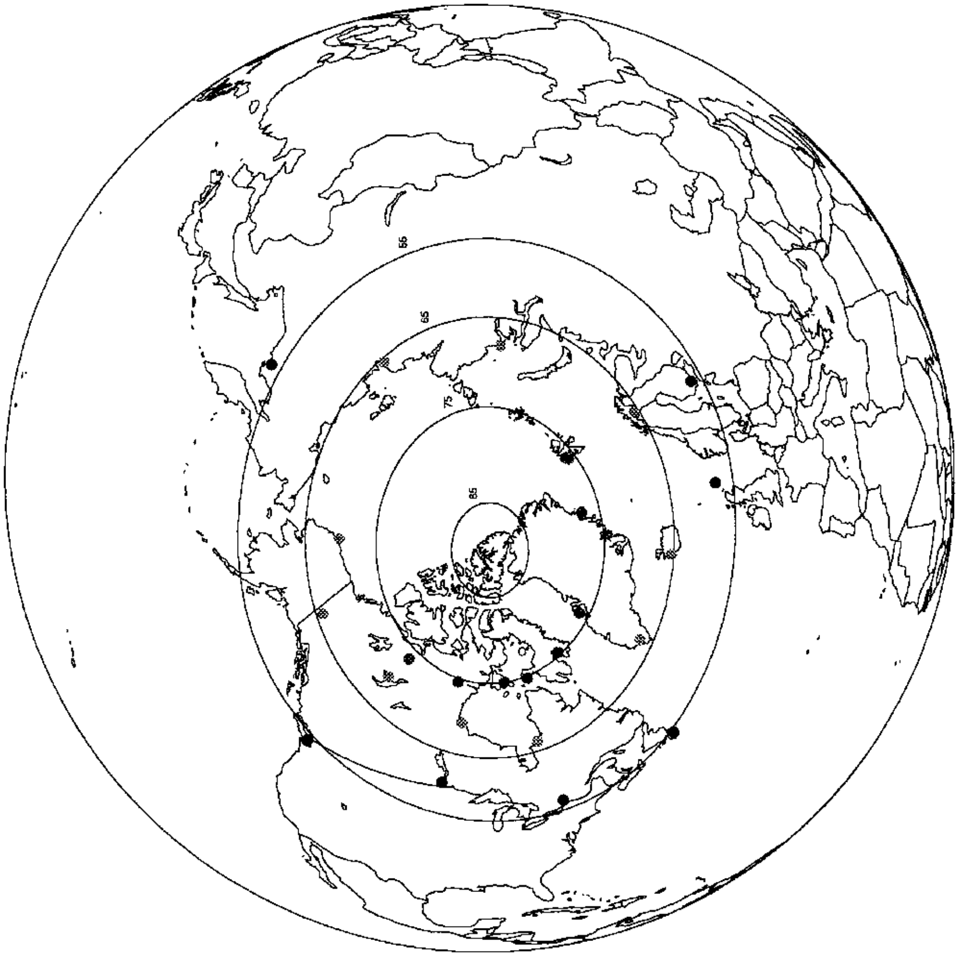

Figure 10. Map of northern hemisphere magnetometer stations which are planned to be used for the derivation of the Contracted, Standard, and Expanded Oval indices, as indicated by the three oval rings.

(Kamide and Akasofu, 1983). We plan to tackle this drawback by using two other (though less complete) rings of magnetometer stations in (i) very high and (ii) sub-auroral latitudes for the construction of complementary indices. These two rings are located at latitudes, where the auroral oval is typically observed when it is either more contracted or more expanded than the standard average oval. Consequently we name the complete new family of indices SO-, CO-, and EO-index for the Standard, Contracted, and Expanded Oval, respectively. The locations of stations which will be used for these three indices are given Figure 10.

For all three indices we will use the same procedure as described above, i.e., construct a preliminary local index as soon as data are available, and update as more data are received. Using this procedure it may eventually be even possible to add data from additional or new stations to these indices, thereby improving the longitudinal sensitivity, at least in regions where enough stations are available. As described above, small substorms, multiple substorm intensifications, and small-scale dayside magnetic disturbances are prime topics for coordinated Cluster and ground-based studies, and a denser index network will eventually allow the recognition of many more such events.

Using the CGB-DC facilities on WWW (see above), it will be possible to view the current Standard, Contracted and Expanded Oval Indices, and decide whether they are useful for the intended study. In order to improve the understanding and information content of the datasets we will not only indicate the actual stations from which data have been included, but also indicate which station produces the maximum envelope portion of the index curve, allowing the user to locate events and follow their motion in longitude or magnetic local time (MLT). An example of such a preliminary summary index plot is given in in Figure 11. In the panels below the index curves, the stations from which data have been included are denoted by thin lines, and those contributing to the envelope function of the final indices are marked with thicker bars. In plots like the one in Figure 11, the relative size of the three indices will be useful for the analysis of the energy state of the magnetosphere, as characterised by the latitudinal location of the maximum electrojet activity at any one MLT. It will also be possible to follow a substorm expansion in latitude, for example when starting off in the standard oval (SO-index) and expanding into the contracted oval index (CO). In our example of December 24, 1995 such an event can be seen from 18:00 to 22:00 UT. Another event on the same day at 10:00 UT shows a disturbance in the standard oval which does not expand to the contracted oval in the same longitude sector. It will thus be possible to discriminate multiple onsets in the standard oval, from expansion phase intensifications of the poleward edge of the substorm bulge. During extremely disturbed times (i.e., under major magnetic storms) much of the variability of the magnetosphere will become visible in the EO-index (no example available yet), and during more quiet times the CO-index will allow the recognition of small substorms or alternatively dayside magnetic disturbances.

We believe that both the more timely availability and better latitudinal coverage of this new family of geomagnetic disturbance indices will be of value for the Cluster ground-based coordination. Event selection for prime orbits can commence roughly one month after its occurrence, and the index used in the scientific evaluation of the event will eventually improve in quality – but not necessarily change in its principal content – as the study converges towards publishable results.

Dayside magnetic disturbances have recently been recognized as important signatures of magnetospheric reconfigurations caused by changes in the solar wind/magnetosphere coupling (see Section 3.2 above). Usually these disturbances are much smaller than typical nightside disturbances – a few 100 nT as compared to substorm disturbances of up to 1000 nT. Consequently they will either disap-

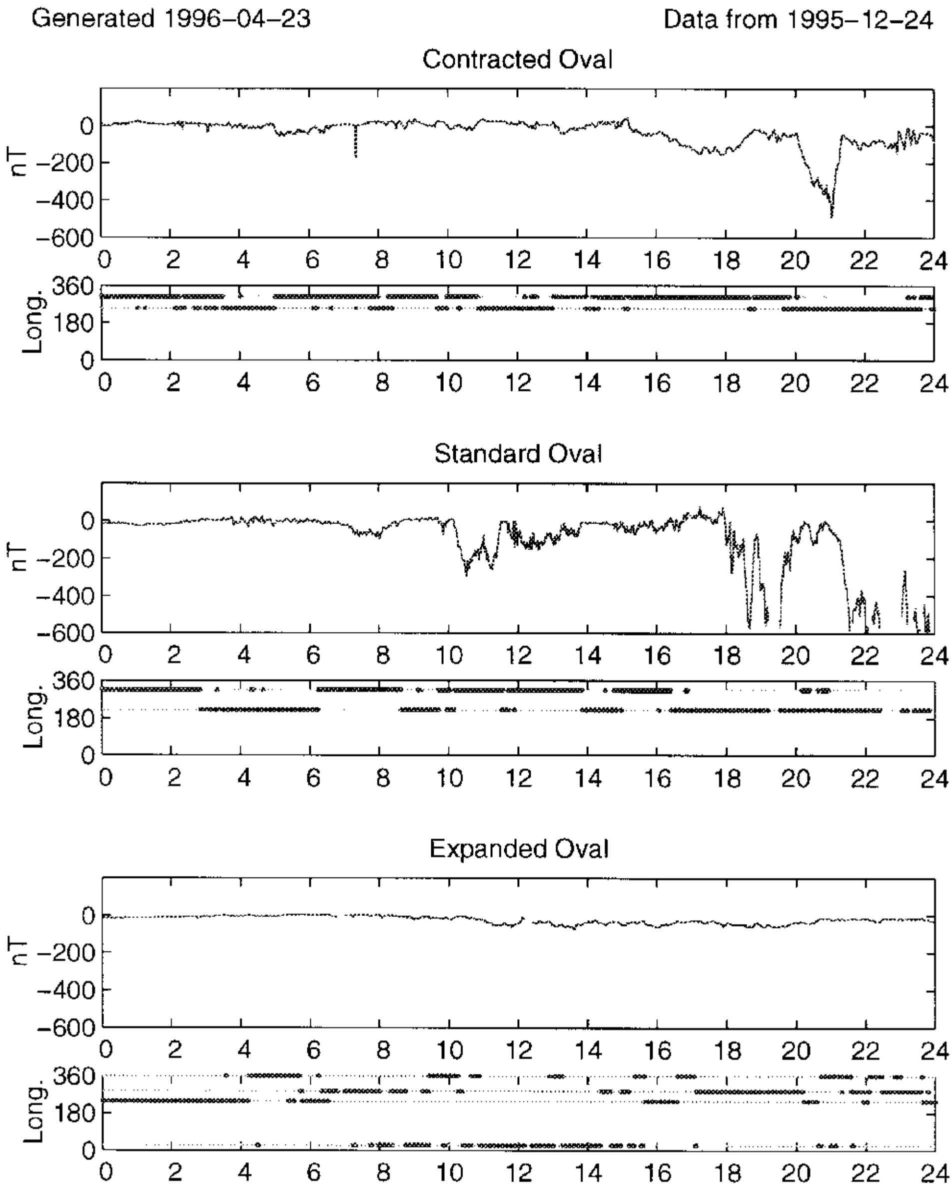

Figure 11. Example plot of the Contracted, Standard, and Expanded Oval indices. Below the index plots all stations contributing to the index are indicated. The station that contributes to the envelope function of the actual index is marked with a heavier bar. Plots based on roughly this number of stations will be available one month after the date in question and will subsequently be upgraded as data from further stations are received.

pear within the normal index envelope or not affect Standard Oval index stations because of their occurrence at cusp latitudes, which corresponds to our new CO-index latitude. The new CO-index, with the station contributing to the envelope clearly marked, will allow the identification of such dayside disturbances and discriminate them from nightside disturbances. This development would thus widen the applicability of the new indices for event selection during the Cluster mission.

In conclusion, we consider this new family of magnetospheric disturbance indices not only to be particularly useful for the Cluster mission, but also for similar coinciding and future missions or dedicated ground-based measurement campaigns. We would like to stress, however, that our new family of indices is not meant to be a substitute for the existing AE-index. They are derived in far too crude a manner (mainly due to lack of time and manpower) to replace AE in detailed quantitative studies. For example, because of the need for rapid compilation with minimal manual intervention we use an automated background subtraction algorithm. We would like to point out that the new CGBDC indices are basically intended for the rapid evaluation of conditions which may have significant implications for:

(a) event selection for coordinated Cluster and ground-based studies,

(b) the operations planning of coordinated Cluster / ground-based observations, and

(c) the operations planning of the Cluster mission itself.

For example, at some instance it might be important to have an estimate of how many substorms were seen while Cluster was at apogee in the tail, when deciding on future operation modes for the following passes.

6. Conclusions

We have reviewed a small fraction of opportunities, where ground-based observations can be used to support the Cluster mission to maximum effect. We have also briefly reviewed some combined satellite and ground observations carried out in the past, and suggested objectives to stimulate thinking about the variety of measurements which could be carried out with a true multi-satellite mission concept. This review is far from complete, but examples have been selected to illustrate the range of uses of ground-based data and the potential to support Cluster observations. Again it should be noted that from the many selected configurations many examples are not even close to magnetic conjugacy between the satellites and key ground-based observatories or networks. Instead often an offset is planned to allow for special coordinated measurements of travelling phenomena, to allow cause and effect studies, as e.g., the dayside activity monitored by Cluster, and possibly associated nightside disturbances monitored by ground-based equipment on the nightside.

We have also illustrated how data from global networks, e.g. magnetometers and large scale HF radarsystems, can be useful not only for dedicated conjugated studies, but to provide a background information on the spatial and temporal large scale state of the magnetosphere, thereby allowing to interprete the Cluster observations within the correct context. This line of thoughts has lead to the development of new magnetic disturbance indices, which are more readily available and more adaptive to different states of the magnetosphere then the widely used AE (or AU and AL indices). Such index and other ground-based summary data will be available for the Cluster mission from the Cluster Ground-Based Data Center at RAL.

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