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Opportunities for Magnetospheric Research Using EISCAT/ESR and Cluster

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The four Cluster spacecraft offer a unique opportunity to study structure and dynamics in the magnetosphere and we discuss four general ways in which ground-based remote-sensing observations of the ionosphere can be used to support the in-situ measurements. The ionosphere over the Svalbard islands will be studied in particular detail, not only by the ESR and EISCAT incoherent scatter radars, but also by optical instruments, magnetometers, imaging riometers and the CUTLASS bistatic HF radar. We present an on-line procedure to plan coordinated measurements by the Cluster spacecraft with these combined ground-based systems. We illustrate the philosophy of the method, using two important examples of the many possible configurations between the Cluster satellites and the ground-based instruments.

1. Introduction

One of the most active areas of solar-terrestrial physics research in recent years has been the study of transient events and rapid temporal changes in the magnetosphere-ionosphere system. 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 either spatial-temporal ambiguity (at low altitudes) or from limited spatial coverage (at high altitudes). For both remote sensing and in-situ measurements there is a compromise struck 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 instrument sensitivity and noise levels and by the orbital dynamics of the satellite; for spatially-integrating ground-based instruments (like magnetometers) it is set by instrument and noise characteristics and 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 (Schmidt and Goldstein, 1988), flying in known but variable configurations (Rodriguez-Canabal *et al.*, 1993; Balogh *et al.*, 1993). However, they will only answer questions on certain temporal and spatial scales, depending on their separation vectors 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.

In terms of the number of geophysical parameters measured, the most powerful of the ground-based observatories are the incoherent scatter (IS) radars, which can be used to measure ion drifts (electric fields), ion and electron temperatures and plasma density. With models and complex processing, the radars also 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 Sondrestrømfjord, Millstone Hill and EISCAT. The range and flexibility of these radars allows detailed measurements to be made which will be exciting complements to the Cluster observations. However, it will be important to match the 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, the antenna scanning pattern appropriate to each study will be needed. Similarly, the right balance between spatial and temporal resolution will need to be struck by the antenna scanning pattern and the pulse coding scheme. A key point about the operation of IS radars is that they require much maintenance and cannot operate on a continuous basis. Therefore detailed planning is required to ensure that the best opportunities for combined studies with Cluster are exploited.

In addition, HF backscatter radars can provide vital 2-dimensional snapshots of the convective flow (Hanuise *et al.*, 1993) and the SUPERDARN network, currently under construction, will image such flow patterns over a large fraction of the high-latitude region in the northern hemisphere. In addition, a tri-static system is planned in the Southern hemisphere, allowing conjugate studies. These systems can take data almost continuously; however, operations planning is still required as they can employ a variety of modes and it will be important that the scan patterns selected are the most appropriate to the combined observations. There are also a wide variety of ground-based optical instruments, which can reveal transient events and track evolving boundaries. Networks of magnetometers, imaging riometers, and digital ionosondes all have many other important applications including monitoring the latitude of the auroral oval as well as the extent and intensity of disturbances along it. Some of these ground-based instruments run continuously, whereas others are operated on a campaign basis. Campaigns will require careful planning if the scientific return with Cluster observations are to be maximised. In this paper we do not wish to review the many capabilities of all these instruments. Rather we wish to present and explain a procedure which aims to ensure that they will be used to maximum effect during the Cluster mission. Particular emphasis is here placed on the planning for the EISCAT and ESR radar systems.

From a survey of the literature we have defined four classes of scientific investigations, employing simultaneous satellite and ground-based observations. We do not attempt to review all such measurements here, but give selected examples to illustrate the classes of scientific application of the data obtained and to look at their potential for Cluster-EISCAT/ESR observations.

1.1 Resolution of spatial and temporal variations

The ground-based observations can extend the range of time scales of temporal variations studied and will also be useful for interpolating between the 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 and field aligned currents in what we now know to be 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, 1995). 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 string 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 (Lockwood, 1995a). 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.

An example of a corresponding nightside phenomenon which has been studied with combined satellite and ground-based observations is the velocity-dispersed ion structures (VDIS) which are thought to be related to the plasma sheet boundary layer (PSBL) in the tail and to result from newly-closed field lines accelerating Earthward (Onsager and Mukai, 1995). Senior *et al.* (1994) used combined satellite and bistatic HF radar data to show that the poleward (high-energy) edge of such an ion dispersion feature (which thus should lie immediately equatorward of the open-closed field line boundary) was at a relatively stable convection reversal boundary, showing spatial structure. On the other hand, de la Beaujardiere *et al.* (1994) used additional IS Sondrestrømfjord radar data to show that the VDIS was also associated with a series of equatorward-drifting arcs, revealing an association with some temporal variations which they interpret as pulses of enhanced reconnection rate in the tail. A demonstration of the value of remote sensing of these features has been given by Elphinstone *et al.* (1995). They showed that the VDIS was associated with the poleward part of a double oval configuration, as seen by the global UV auroral imager on the VIKING satellite. Subsequent to the pass of the low-altitude satellite which observed both the VDIS and the lower-latitude "central plasma sheet" (CPS), the imager observed that a substorm expansion took place on the auroral oval associated with the CPS precipitation, several degrees equatorward of the VDIS and thus well equatorward of the open/closed boundary.

1.2 Placing satellite observations in context

We will also be able to use ground-based observations to place the Cluster measurements 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 in which regions of the magnetosphere-ionosphere system the spacecraft were. In addition sequences of changes, as for example during substorms, can be monitored from the ground. Thus ground-based data can be used to define where both events and spatial structures, seen by spacecraft, were in both time and space. An example of placing a spatial structure in context of the larger-scale spatial distribution is the work on the dayside field-aligned currents and magnetosheathlike plasma precipitations by de la Beaujardiere *et al.* (1993). They used radar observations of the convection pattern to determine which convection cell a satellite passed through, and thus to resolve an ambiguity between two proposed spatial distributions of field-aligned currents. Ground-based data can be used to place small-scale features into spatial context with the major substorm features, in the same way in which Fujii *et al.* (1994) used such information from global UV imagers. 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 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.

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 groundbased observations of substorm onset to show that tail lobe field strengths begin to decay at onset, implying 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 onset is Earthward of, and before, significant closure of open flux by tail reconnection. It is clear that the resolution of these conflicting observations, and of this general debate between the "classical near-Earth neutral line" and "Kiruna conjecture" models, will require combinations of ground-based and satellite data (see review by Lockwood, 1995b).

1.3 Providing boundary conditions

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, 1992). 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, 1991); 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, 1995) 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).

2. Planning Procedures

In order to plan coordinated observations using Cluster and ground-based facilities, ESA established a working group (Opgenoorth, 1993) for which we act as chairman (HJO) and the representative for incoherent scatter facilities (ML). The working group has met several times and organised a workshop in Orleans, France in March 1994, with a second in Rome in April 1995. As an initial basis for planning, the working group has followed ESA's Cluster Science Plan by dividing all satellite orbits so that their apogee falls into one of four magnetic local time (MLT) sectors, namely 6 hours around 0 MLT, 6 MLT, 12 MLT and 18 MLT (i.e. the midnight, dawn, noon and dusk sectors). We also consider the ground-based station or meridian chain, in this case the combined EISCAT and ESR radars, to be simultaneously 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 EISCAT/ESR 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 craft: this should not be confused with the configurations of the four craft, relative to each other, which is variable but an important and complex part of the operations planning for the Cluster mission itself (Rodriguez-Canabal *et al.*, 1993). The numbers in Fig. 1 refer to those configurations/ conjunctions which we have identified for periods when the Cluster orbit plane is close to the noon-midnight (GSE XZ) plane, whereas those in Fig. 2 are when the orbit plane is closer to the dawn-dusk (GSE YZ) plane. Figure 1 views the Earth and the Cluster orbit (thick line) from dusk and the small arrow shows the location of 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 tail neutral sheet. Figure 2 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

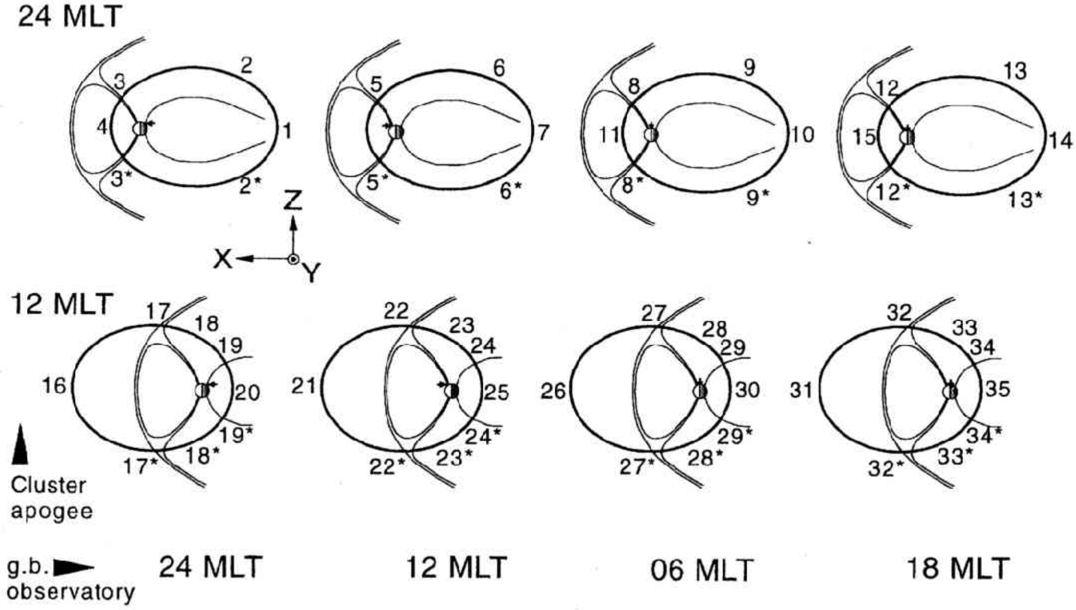

Fig. 1. Cluster orbits for when the orbit plane is close to the noon-midnight (GSE XZ) plane. The Earth and the Cluster orbit (thick line) are viewed from dusk and the small arrow shows the location of a ground observatory (in this case EISCAT/ESR). The thin lines show a typical magnetopause location, along with geomagnetic field lines which thread the dayside low-latitude boundary layer (LLBL), the high latitude boundary layer (HLBL or mantle) and the tail neutral sheet. The numbers refer to satellite locations for configurations/conjunctions with the ground observatory which we have identified to be of particular scientific interest (see Table 1). The upper row of four figures are all for orbits with 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 at time when the satellite is at the numbered location (from left to right, the plots in each horizontal row are for the ground-based observatory in the midnight, dawn, noon and dusk sectors). 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 are denoted with an asterix.

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 Fig. 1. 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 groundbased observations of the development of the substorm aurora and electrojets in the midnight sector while Cluster makes simultaneous observations in the tail lobe. In Figs. 1 and 2 we label configurations where EISCAT/ESR 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).

We have made an initial assessment of a list of potential scientific objectives for each numbered conjunction/configuration, as given in Table 1. The lists of characters refer to scientific objectives and areas of study toward which the combination of EISCAT/ESR and Cluster is expected to make a significant and unique contribution. Table 2 is a key to these characters: lower case arabic characters are

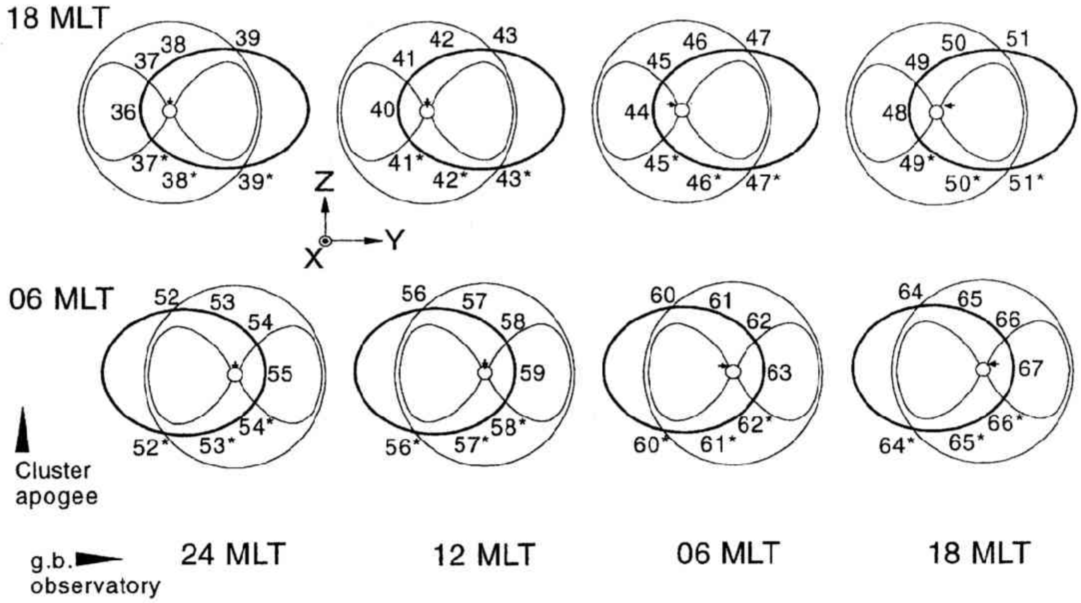

Fig. 2. Corresponding plots to Fig. 1, for when the orbit plane is close to the dawn-dusk (GSE YZ) plane, so that satellite apogee is in the dusk sector (upper row) or the dawn sector (lower row). The Earth and the Cluster orbit (thick line) are viewed from the sun and the thin lines show a typical magnetopause and field lines which pass through the low-latitude boundary layer on the dawn and dusk flanks of the magnetosphere.

areas of study concerned with one of the major objectives of the Cluster mission, namely substorms; upper case arabic characters refer to more general areas of magnetospheric topology, dynamics and morphology; and greek characters refer to studies of the magnetopause boundary layers, including the other major Cluster objective, the cusp. As will be discussed in Section 4, each configuration/conjunction is likely to occur (within 3-hour MLT tolerances) of order 3 or 4 times per year. Nevertheless, this leads to a great many opportunities for combined observations. If, for example, we require an average of 6 hours EISCAT/ ESR measurements for each of the 102 configurations (including those with Cluster in the opposite hemisphere) shown in Figs. 1 and 2, this would require at least $(6 \times 3 \times 102) = 1836$ hours of radar operations. Given that for nearly all the scientific objectives it is vital that the ESR operate simultaneously with both the EISCAT UHF and the VHF systems, this is unlikely to be achievable. In addition, the 4 Cluster craft will only be able to take high-resolution ("burst mode") data for a limited portion of each orbit, due to tracking limitations and on-board recording capacity. Hence for planning (both from the point of view of EISCAT/ESR and the Cluster Science Working Team, SWT), it is necessary to prioritise these possibilities. Table 1 also gives our initial assessment of the priorities, by selecting those that we see as very high priority (VHP) and high priority (HP).

These lists are still under discussion by the working group and will be extended and amended as the planning proceeds. In order to achieve this, an interactive implementation of Figs. 1 and 2 and Tables 1 and 2 can be accessed via the worldwide web (WWW, the required URL is http://wdcc1b.bnsc.rl.ac.uk/). To make full use of these pages, a image-handling browser like Mosaic is needed. These pages allow suggested corrections and additions to be logged and the staff of World Data Centre C1 at RAL will maintain, correct and update the list after consultation with the relevant working group members. Hence this implementation provides a way for the world-wide community of ground-based researchers to refine and extend these planning options.

These WWW pages also give information on when any one of the conjunctions or configurations shown in Figs. 1 and 2 will occur, for any user-specified ground-based observatory. This information is

Table 1. Ground based-cluster experiments.

#		Ground-based site location	Cluster location	Scientific objectives (see Table 2)
1	VHP	midnight AO and PC	tail NS	a,b,c,d,e,f,g,h,i,j,A,l,m,r,s,t,H,k,n,v,B,w
2	HP	midnight AO and PC	lobe	c,f,g,h,A,m,G,r,s,t,J,v,C,w
2*		midnight AO and PC	lobe	c,f,g,h,G,r,s,t,J,v,C,D,w
3		midnight AO and PC	interior cusp	o,r,u
4		midnight AO and PC	dayside RC	p,q,j,E,F
5	VHP	cusp/cleft	interior cusp	α,Ω,π,β,γ,δ,ε,ζ,η,θ,Λ,σ,λ,τ,ξ,Δ,μ,A,J,G,Θ,Σ
5*	HP	cusp/cleft	interior cusp	α,Ω,π,β,γ,δ,ζ,Λ,A,D,Θ,Δ,μ,J
6	HP	cusp/cleft	lobe	r,α,Ω,π,ξ,τ
6*		cusp/cleft	lobe	r,α,Ω,π,ξ
7		cusp/cleft	tail NS	o,r,l,τ
8	HP	dawn AO and PC	interior cusp	μ,ξ,Λ,θ,r,G,s
8*		dawn AO and PC	interior cusp	r,s
9		dawn AO and PC	lobe	r,s,t,G,c,C,f,v,B,k,w
9*		dawn AO and PC	lobe	r,s,t,c,f,k,v,B,w
10	HP	dawn AO and PC	tail NS	r,s,t,k,w
11		dawn AO and PC	dayside RC	q,p,s,t,E,F,w
12	HP	dusk AO and PC	interior cusp	Δ,μ,ξ,Λ,θ,r,s
12*		dusk AO and PC	interior cusp	r,s
13		dusk AO and PC	lobe	r,s,t,G,n,v,B,w
13*		dusk AO and PC	lobe	r,s,t,n,v,B,w
14	HP	dusk AO and PC	tail NS	r,s,t,c,f,n,v,B
15		dusk AO and PC	dayside RC	q,p,s,t,E,F,χ,j
16		midnight AO and PC	SW	u,I
17		midnight AO and PC	exterior cusp	u,o,J,r
17*		midnight AO and PC	exterior cusp	u,o,J,r
18		midnight AO and PC	near-Earth lobe	c,f,G,C,J
18*		midnight AO and PC	near-Earth lobe	c,f,G,C,J
19	HP	midnight AO and PC	midnight AO	H,i,j,A,B,r,v,k,n,e
19*		midnight AO and PC	midnight AO	B,r,v,k,n,e
20		midnight AO and PC	nightside RC	p,q,E
21	HP	cusp/cleft	SW	δ,ε,ξ,Θ,Λ,α,Ω,π,Σ,Γ,ψ
22	VHP	cusp/cleft	exterior cusp	α,Ω,π,β,γ,δ,ε,Θ,η,θ,Λ,A,σ,μ,τ,ξ,φ,ψ,Γ,Δ,Ξ,Σ
22*	HP	cusp/cleft	exterior cusp	α,Ω,π,β,γ,δ,η,Λ,A,σ,μ,τ,ξ,ψ,Γ,Δ,D,Ξ,Σ
23	HP	cusp/cleft	near-Earth lobe	r,τ,ξ,Δ,G,C,J,A
23*		cusp/cleft	near-Earth lobe	r,τ,ξ,Δ,G,C,J,D
24		cusp/cleft	midnight AO	o,J,G,r,v
24*		cusp/cleft	midnight AO	o,J,G,r,v
25		cusp/cleft	midnight RC	o,p,q,τ
26	HP	dawn AO and PC	SW	s,r,t,u,I,J,k,θ,Λ,λ,μ,ξ,ψ,Γ,G
27	VHP	dawn AO and PC	exterior cusp	s,r,u,I,J,k,α,Ω,π,β,γ,δ,θ,Λ,σ,λ,μ,ξ,φ,ψ,Γ,G,Σ
27*	HP	dawn AO and PC	exterior cusp	s,r,u,I,J,k,α,Ω,π,β,γ,δ,θ,Λ,λ,μ,ξ,φ,ψ,Γ,D,G,Σ
28	HP	dawn AO and PC	near-Earth lobe	s,t,r,B,τ,f,c,G,J,C,w
28*		dawn AO and PC	near-Earth lobe	s,t,r,B,f,c,G,J,C,w
29		dawn AO and PC	midnight AO	s,t,r,B,e,k,w
29*		dawn AO and PC	midnight AO	s,t,r,B,e,k,w
30		dawn AO and PC	midnight RC	p,q,s,t,r,E
31		dusk AO and PC	SW	s,r,t,u,I,J,k,θ,Λ,λ,μ,ξ,ψ,Γ,χ,G
32	VHP	dusk AO and PC	exterior cusp	s,r,u,I,J,α,Ω,π,β,γ,δ,θ,Λ,σ,λ,μ,ξ,φ,ψ,Γ,χ,G,Σ,Ξ
32*	HP	dusk AO and PC	exterior cusp	s,r,u,I,J,α,Ω,π,β,γ,δ,θ,Λ,λ,ξ,φ,ψ,Γ,D,χ,G,Σ,Ξ
33	HP	dusk AO and PC	near-Earth lobe	s,t,r,B,χ,f,c,C,G,J,w
33*		dusk AO and PC	near-Earth lobe	s,t,r,B,χ,f,c,C,G,J,w

Table 1. (continued).

#		Ground-based site location	Cluster location	Scientific objectives (see Table 2)
34		dusk AO and PC	midnight AO	s,t,r,B,e,n,χ,o,w
34*		dusk AO and PC	midnight AO	s,t,r,B,e,n,χ,o,w
35		dusk AO and PC	midnight RC	p,q,s,t,r,χ,E,n,w
36		midnight AO and PC	dawn RC	p,q,E,k,w
37		midnight AO and PC	dawn AO	r,s,t,B,k,v,w
37*		midnight AO and PC	dawn AO	r,s,t,B,k,v,w
38	HP	midnight AO and PC	near-Earth lobe	s,t,r,f,c,B,C,J,G,v,w
38*		midnight AO and PC	near-Earth lobe	s,t,r,f,c,B,C,J,G,v,w
39		midnight AO and PC	dusk MP	I,u,o
39*		midnight AO and PC	dusk MP	I,u,o
40		cusp/cleft	dawn RC	r,p,q,E
41	HP	cusp/cleft	dawn AO	r,B,α,Ω,π,β,δ,θ,Λ,A,σ,λ,μ,ξ,Δ
41*		cusp/cleft	dawn AO	r,B,α,Ω,π,β,δ,θ,Λ,A,σ,λ,μ,ξ,Δ
42	HP	cusp/cleft	near-Earth lobe	r,r,ξ,τ,G,J,C,a,Ω,π
42*	HP	cusp/cleft	near-Earth lobe	r,ξ,τ,G,J,C,a,Ω,π,D
43	VHP	cusp/cleft	dusk MP	A,α,Ω,π,Ξ,β,γ,δ,θ,Λ,σ,λ,ξ,φ,ψ,Γ,Δ,Θ,ε,η
43*	VHP	cusp/cleft	dusk MP	A,α,Ω,π,Ξ,β,γ,δ,θ,Λ,σ,λ,ξ,φ,ψ,Γ,Δ,Θ,D
44		dawn AO and PC	dawn RC	p,q,E,s,t,r,A,m,k,v,B
45	VHP	dawn AO and PC	dawn AO	H,r,s,t,k,θ,λ,Λ,σ,α,Ω,π,A,m,v,B,w
45*		dawn AO and PC	dawn AO	r,s,t,k,θ,λ,Λ,σ,α,Ω,π,A,m,v,B,w
46	HP	dawn AO and PC	near-Earth lobe	r,s,t,k,c,f,J,G,B,C,m,v,μ,ξ
46*		dawn AO and PC	near-Earth lobe	r,s,t,k,c,f,J,G,B,C,m,v,μ,ξ
47		dawn AO and PC	dusk MP	r,s,t,Γ,σ,I,φ,ψ,u,Λ
47*		dawn AO and PC	dusk MP	r,s,t,Γ,σ,I,φ,ψ,u,Λ
48		dusk AO and PC	dawn RC	p,q,r,s,t,E
49		dusk AO and PC	dawn AO	r,s,t,Λ,v,B
49*		dusk AO and PC	dawn AO	r,s,t,Λ,v,B
50	HP	dusk AO and PC	near-Earth lobe	r,s,t,n,c,f,J,G,B,C,χ,m,v,μ,ξ
50*		dusk AO and PC	near-Earth lobe	r,s,t,n,c,f,J,G,B,C,χ,m,v,μ,ξ
51	VHP	dusk AO and PC	dusk MP	r,s,t,B,χ,θ,λ,Λ,σ,ψ,Γ,φ,n,A,Ξ
51*	HP	dusk AO and PC	dusk MP	r,s,t,θ,λ,Λ,σ,ψ,Γ,φ,n,D,Ξ
52		midnight AO and PC	dawn MP	I,u
52*		midnight AO and PC	dawn MP	I,u
53	VHP	midnight AO and PC	near-Earth lobe	s,t,r,f,c,B,C,J,G,g,i,v,B,w
53*		midnight AO and PC	near-Earth lobe	s,t,r,f,c,B,C,J,G,g,i,v,B,w
54		midnight AO and PC	dawn RC	χ,e,n,m,t,w
54*		midnight AO and PC	dawn AO	χ,e,n,m,t,w
55		midnight AO and PC	dawn AO	p,q,E,F,e,g,i,j,l,m,B,v
56	VHP	cusp/cleft	dawn MP	A,α,Ω,π,Ξ,β,γ,δ,θ,Λ,σ,λ,ξ,φ,ψ,Γ,Δ,Θ,ε,η
56*	VHP	cusp/cleft	dawn MP	A,α,Ω,π,Ξ,β,γ,δ,θ,Λ,σ,λ,ξ,φ,ψ,Γ,Δ,Θ,ε,η
57	HP	cusp/cleft	near-Earth lobe	r,ξ,τ,G,J,C,α,Ω,π,A
57	HP	cusp/cleft	near-Earth lobe	r,ξ,τ,G,J,C,α,Ω,π,D
58	HP	cusp/cleft	dusk AO	r,s,n,B,α,Ω,π,β,ζ,θ,Λ,A,σ,λ,μ,ξ,Δ,χ
58*		cusp/cleft	dusk AO	r,s,n,B,α,Ω,π,β,ζ,θ,Λ,A,σ,λ,μ,ξ,Δ,χ
59		cusp/cleft	dusk RC	p,q,E,F,τ,r
60	VHP	dawn AO and PC	dawn MP	r,s,t,B,θ,λ,Λ,σ,ψ,Γ,φ,k,A,Ξ
60*	HP	dawn AO and PC	dawn MP	r,s,t,θ,λ,Λ,σ,ψ,Γ,φ,k,D,Ξ
61	HP	dawn AO and PC	near-Earth lobe	r,s,t,k,c,f,J,G,B,C,χ,m,v,μ,ξ,w
61*		dawn AO and PC	near-Earth lobe	r,s,t,k,c,f,J,G,B,C,χ,m,v,μ,ξ,w

Table 1. (continued).

#		Ground-based site location	Cluster location	Scientific objectives (see Table 2)
62		dawn AO and PC	dusk AO	r,s,t,v,B,Λ,w
62*		dawn AO and PC	dusk AO	r,s,t,v,B,Λ,w
63		dawn AO and PC	dusk RC	p,q,r,s,t,E,F,w
64		dusk AO and PC	dawn MP	r,s,t,Γ,σ,I,ϕ,ψ,u,Λ,χ
64*		dusk AO and PC	dawn MP	r,s,t,Γ,σ,I,ϕ,ψ,u,Λ,χ
65	HP	dusk AO and PC	near-Earth lobe	r,s,t,n,c,f,J,G,B,C,m,v,μ,ξ,w
65*		dusk AO and PC	near-Earth lobe	r,s,t,n,c,f,J,G,B,C,m,v,μ,ξ,w
66	VHP	dusk AO and PC	dusk AO	H,r,s,t,n,θ,λ,Λ,σ,A,v,B,m,χ,w
66*		dusk AO and PC	dusk AO	r,s,t,n,θ,λ,Λ,σ,D,v,B,m,χ,w
67		dusk AO and PC	dusk RC	p,q,E,F,s,t,r,A,m,n,v,B,χ,w

abbreviations: AO = auroral oval; HP = high priority; MP = magnetopause; NS = neutral sheet; PC = polar cap; RC = ring current; SW = Solar Wind; VHP = very high priority Configuration numbers labelled * have satellites in opposite hemisphere to ground-based site.

based on the most recent orbital data from the Cluster Joint Science Operations Centre (JSOC) at RAL (Dunford *et al.*, 1993) and makes use of the Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM) system and software (Gustafsson *et al.*, 1992; Baker and Wing, 1989). Prior to launch, the exact Cluster orbit is unknown and the predictions will only be valuable for testing various operational scenarios and software. However, the predictions are regenerated with each user request and, after launch, will always be based on the most recent information and the same orbit predictions as used by the JSOC for planning Cluster operations. We will receive various data from the JSOC once per week. From this we will compile the list of events (for example magnetopause crossings) which are the basis of the predictions which can be obtained via these pages. There will be five classes of orbit and operations predictions for any date and UT (time t):

T. Pre-launch test scenario data (code T for test)
I. Initial plans at $t - 6$ months (code I for initial)
R. Refined plans at $t - 4$ months (code R for refined)
A. Agreed plans at $t - 2.5$ months (code A for agreed)
F. Final plans at $t - 2$ weeks (code F for final)

The refined (R) plans may differ from the initial plans (I) because of orbit manoeuvres and will form the basis of Cluster Science Working Team discussions, held roughly every 3 months. The result of these discussions are the agreed plans (A), to which JSOC will only make minor adjustments to meet operational constraints, before the final plans (F) are approved by the project scientist and transmitted to the spacecraft. For any one configuration with a certain ground observatory site, the predictions given will always be the most up to date, and will carry the T, I, R, A, or F status flag.

In addition, we hope to arrange a fifth classification with JSOC:

P. Post-observation data at $t + 1$ month (code P for post)

These will be very useful in exploiting the data after they are acquired.

The WWW pages will also allow ground-based experimenters to record their most recent plans for observation times and modes, based on these predictions, which will be automatically passed on to JSOC. The T, I and R predictions will enable us to make provisional plans for our ground-based facilities. These will be used by HJO at Cluster SWT meetings to try to ensure that Cluster data are, wherever possible, taken in the desired modes (normal or burst) at the desired segment of the orbit, with the four satellites in the desired constellation and orientation. The A and F plans will allow us to, respectively, decide upon and finalise our operating schedules but are for information only: it is extremely unlikely that we will be

Table 2. Scientific objectives.

Tail phenomena and substorms	
a.	Location of substorm onset
b.	Location of near-Earth neutral line (NENL)
c.	Onset time of substorm-enhanced tail reconnection
d.	Mechanisms for cross-tail current disruption (CD)
e.	Development of CD and evolution into NENL
f.	Energy release from tail lobe
g.	Pseudobreakups
h.	Structure,evolution and pinch-off time of plasmoids
i.	Equatorward-drifting arcs
j.	Nightside ionospheric outflows and tail composition
k.	Omega bands
l.	Plasma sheet (PS) thinning
m.	Field aligned currents and precipitation as a function of substorm phase
n.	Westward travelling surge
o.	Connection of dayside and nightside auroral intensifications
p.	Asymmetric ring current
q.	Energetic particle injection
r.	Substorm growth phase
s.	Polar cap expansion and contraction
t.	Convection during substorms
u.	IMF and SW triggers of substorms
v.	Recovery phase
w.	Activations along a contracted auroral oval
General magnetospheric topology, morphology and dynamics	
A.	Mapping electric and magnetic fields
B.	Double auroral oval and open/closed boundary
C.	Lobe field topology (bifurcation and asymmetries)
D.	Conjugacy and interhemispheric symmetries and asymmetries
E.	Time-dependency of RC drift shells and splitting
F.	Detached plasmasphere regions and ionospheric plasma in the dayside magnetosphere
G.	Transpolar and other polar cap arcs
H.	Auroral acceleration
I.	IMF control of convection
J.	NBz convection

able to influence the Cluster data-taking strategy after $t - 3$ months, and the earlier we know of the provisional plans for the ground-based facility, the more chance there is of accommodating them with those of SWT and JSOC.

3. Examples of Very High Priority Cases

The permutations of science topics and satellite-ground configurations listed in Table 1 are far too numerous to explain here in detail. However, to illustrate the choice of scientific objectives and the priorities, we here explain our thinking for just two cases. 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 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 Table 1.

3.1 Studies of nightside magnetospheric disturbances and substorms

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

Table 2. (continued).

Magnetopause and boundary-layers	
α.	Effects of magnetopause reconnection
β.	Location of dayside X-line
γ.	Conditions at dayside X-line
δ.	Causes of magnetopause reconnection rate variations
ε.	Ion transmission factors across magnetopause
ζ.	Cusp ions steps and temporal and spatial variations
η.	Maintenance of cusp quasi-neutrality
θ.	Open and closed low-latitude boundary layers (LLBL)
Λ.	Origin,propagation and lifetime of travelling convection vortices (TCVs)
σ.	Field-aligned currents and precipitation in TCVs
λ.	Voltage and thickness of LLBL
μ.	Local time extent of dayside transients
τ.	Origin of cleft ion fountain and effects on lobe and PS composition
ξ.	Voltage contribution of reconnection pulses
ϕ.	Magnetopause oscillations and surface waves
χ.	Mid-afternoon auroral bright spot
ψ.	IMF control of dayside ionospheric transients, TCVs and magnetopause flux transfer events (FTEs)
Γ.	SW pressure pulses as a cause of TCVs, magnetopause FTEs and reconnection pulses
Δ.	Spatial distribution and origins of dayside field aligned current
Θ.	Ion acceleration at the magnetopause
Ξ.	Motion of newly-reconnected field lines
Σ.	Origin of polar cap patches
Ω.	Origin of dayside ionospheric transients
π.	Ionospheric signatures of magnetopause FTEs

shown that substorm-like magnetic activity can occur, even on a highly contracted auroral oval. These weak disturbances are usually not in the field of view for EISCAT, but will be perfectly located for studies by the ESR. The links between these disturbances and magnetospheric processes are still not understood and possible differences from ordinary substorms are of interest. We require observations of the contracted oval by EISCAT/ESR with simultaneous Cluster measurements in the tail lobe or plasma sheet (configurations 2 and 1, respectively). (For these reasons, scientific objectives w, J, o and v from Table 2 are among those listed in Table 1 for configuration 1 of Cluster with the EISCAT/ESR radars).

Other features of the relatively quiet magnetosphere are the so-called "theta" auroras and other sun-aligned arcs (Murphree and Cogger, 1981; Frank *et al.*, 1982; Murphree *et al.*, 1989, 1994; Austin *et al.*, 1993) and auroral structures within the polar cap, such as in the "teardrop" or "horse-collar" aurora (Hones *et al.*, 1989), which may be part of the same general pattern of behaviour. Such features are mostly out of reach for most ground-based auroral zone instrumentation and so their dynamics and possible links to magnetospheric regions and processes have remained a puzzle. They appear to occur during periods of northward-directed IMF (Elphinstone *et al.*, 1990), and hence our relative ignorance of these phenomena is despite the fact that they are associated with a magnetospheric configuration which prevails for 50% of the time. Pellinen *et al.* (1990) have shown that the dynamics of transpolar arcs involve substorm like features, and detailed studies will be possible with the new ESR radar. Understanding the possible underlying magnetospheric processes and topology will be an important topic for Cluster studies in the magnetospheric tail lobes and plasma sheet (scientific objectives G, o, A, B, C, D, G, I, J).

The early development of a substorm is often characterized by equatorward-drifting auroral arcs, indicating enhanced magnetospheric energy storage. They are seen in the late growth phase and early expansion phase, poleward of where onset will later occur or has already occurred, respectively. The origin of these arcs is still not completely understood, but there is some evidence that they originate from Earthward-moving structures within the plasma sheet boundary layer, the northernmost arc being associated with the VDIS and thus inferred to be close to the open/closed field-line boundary (de la Beaujardiere, 1994; Elphinstone *et al.*, 1994, 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 ESR/EISCAT 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). These multiple, equatorward-drifting arcs are of interest for several reasons. They are observed to be associated with considerable ionospheric ion outflows (Wahlund *et al.*, 1989, 1992), which could well populate the near-Earth central plasma sheet with oxygen ions and influence substorm development there (scientific objective j). Their equatorward drift motion was also observed to be unaffected by substorm onset at lower latitudes, at least until the poleward substorm expansion reaches their latitude and they are engulfed by the main substorm aurora. This agrees with the concept of substorm onset occurring in the near-Earth central plasma sheet (CPS) location, such that the boundary plasma sheet (BPS) and plasma sheet boundary layer (PSBL) remain unaffected for at least for the first ten minutes of the expansion phase after onset (see Persson *et al.*, 1994a, b; Gazey *et al.*, 1995). Radar data also indicate that the conductivity they produce can be so large as to initially reduce the local ionospheric electric field to almost zero (Morelli *et al.*, 1993). A similar suppression of the electric field in the high conductivity region of the main substorm expansion has been demonstrated by Weimer *et al.* (1994). Combined satellite ground observations will be essential to investigate both the origins and the effects of these equatorward-drifting arcs (scientific objectives i, j, m, q, r, t).

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 $X=-8R_E$, which is relatively close to the Earth in the central tail current sheet (see Lui *et al.*, 1992, and references therein). This places substorm onset (and the pre-existing auroral oval) at the modelled location of the maximum cross tail current strength (Kaufmann, 1987; Pulkkinen *et al.*, 1992). In contrast to this inferred near-Earth location of onset, signatures of reconnection (specifically plasma flows and the polarity of the magnetic field across the tail current sheet) place the near-Earth neutral line (NENL) somewhere beyond $X=-20R_E$ (Baumjohann *et al.*, 1991; Baumjohann, 1993; Nakamura *et al.*, 1994). This conclusion is very important, because it means 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). In configuration 1, Cluster will pass through the likely region of NENL formation but will, according to the Kiruna conjecture, see the substorm current disruption expanding tailward. EISCAT/ESR, the surrounding Image magnetometer array, and other ground-based instrumentation such as coherent radars and optical imagers, will allow us to monitor the onset and spreading of the current disruption, thereby addressing these key questions. 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 to know 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 in even the later phases of substorm development (in the recovery phase), and these may be associated with the relatively late detachment of a plasmoid. (scientific objectives a–f, h, i, 1, v, B, I).

Ground-based data often show a substorm onset, but which subsequently fails to develop into a full substorm (Lui *et al.*, 1976; Untiedt *et al.*, 1978; Koskinen, 1992). The behaviour of the tail current sheet and the reason for the incomplete substorm development is not yet known (scientific objective g). Similarly it can be shown, by combining ground-based and near-Earth satellite data sets, that 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). We believe that many questions concerning the individual substorm development and the causal sequence of events might be solvable by studying either incomplete substorms (pseudobreakups) or multiple-onset substorms with multipoint measurements in various regions of the ionosphere/magnetosphere system. Recent studies show that there are field changes and flow bursts in the mid tail sometimes seen in association with substorms which appear to be absent in psuedobreakups (Lopez *et al.*, 1994; Catell *et al.*, 1994). Because there is much to be learned about substorms when they are expected but fail to happen, Sergeev *et al.* (1994) and Yahnin *et al.* (1994) have studied the conditions in the ionosphere and in the tail during steady convection events (also called convection bays). The implications for various models of substorm onset have been discussed by Pulkkinen *et al.* (1994).

While Cluster and other satellites study the mid-tail variations during substorms, the radars and other ground-based instrumentation could study the ionospheric convection, precipitation and field-aligned currents, which transfer energy and momentum to the ionosphere (scientific objectives t and m), and monitor the dynamics of the various boundaries. A goal of particular importance is detecting and tracking the development of the open/closed field-line boundary (scientific objectives s and B), not only during the growth and recovery phases of individual substorms, but also during incomplete and multiple substorm intensifications, thus determining the relative importance in terms of magnetospheric energy release. In this respect, high latitude observatories like the ESR will be important for substorms which show features poleward of the main electrojet, as studied by Fox *et al.* (1994), or which expand to very high latitudes (Huang *et al.*, 1994). Other more localized features in the early expansion and late recovery phase are the westward travelling surge and Omega bands which, from an auroral point of view, are the most dominant features in the evening and morning sectors, respectively. While their basic magnetospheric source regions for the features are identified, many questions about their exact mechanisms of formation and dynamic development are still open (see Opgenoorth *et al.*, 1989, 1994) (scientific objectives g, t, m, S, B, I).

There are other scientific questions, not specifically related to substorms, which the configuration 1 will allow us to study. High energy electrons follow trajectories which are close to field-aligned because the field lines onto which they are frozen do not convect far in their time-of-flight. These will be detected by Cluster and can be monitored by the radars from the low-altitude density enhancements they cause. Hence comparing the spatial distributions of high energy electron precipitation seen by the Cluster craft and by the radars may tell us about how field lines map (scientific objective A) and comparing the derived energy spectra could, in principle, tell us about acceleration processes between the spacecraft and the ionosphere (scientific objective H). However, limitations in time and energy resolution of both data sets may not allow firm conclusions to be drawn. Induction effects mean we cannot assume that electric fields map to the ionosphere for short time scale phenomena (Lockwood and Cowley, 1992). For example, the sunward convection surge in the equatorial magnetosphere associated with field line dipolarisation appears not to have an ionospheric counterpart in electric fields. Simultaneous EISCAT/ESR and Cluster observations can help to confirm this allow measurement of the inductive smoothing time constant of the ionospheric flow. Such studies will also be important for understanding the ionospheric convection associated with bursty bulk flow events which appear to be responsible for most of the flux transport in the central plasma sheet (Angelopolous *et al.*, 1992a, b, 1994; Sergeev *et al.*, 1992). (scientific objective A).

3.2 Studies of coupling across the dayside magnetopause

Much recent interest has focused on how and where reconnection takes place at the dayside magnetopause (see reviews by Lockwood (1995a) and 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) should be detected by comparing the ion data from the different

Cluster spacecraft if they intersect the same L-shells at times separated by less than about 10 minutes. 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.*, 1989, 1993a; Sandholt *et al.*, 1990). Not only do combined observations provide valuable confirmation of the theory of the effects of pulsed reconnection, but they allow the location of the reconnection site to be determined, as discussed in Subsection 1.4. Furthermore, the method of Lockwood *et al.* (1994) can be used to compute a variety of important parameters at the reconnection site which may well control the reconnection behaviour (including the local magnetosheath density, temperature, Alfvén speed and field strength, as well as its field-aligned flow speed). Thus the combined observations offer unique opportunities to study the causes of reconnection rate changes (scientific objectives α, Ω, π, β, γ, δ and ζ).

In addition, comparisons with simultaneous interplanetary measurements from the WIND and IMP-8 satellites will allow us to study the percentage of ions which are transmitted across the rotational discontinuity near the deduced reconnection site, as well as their consequent acceleration and any heating (objectives ε and Θ). Experimental estimates of the transmission factor have varied from 0.5 (Fuselier *et al.*, 1991) to 0.1 (Onsager *et al.*, 1995) and measurements of the distribution functions of the accelerated ion flows by Smith and Rodgers (1991) are in close quantitative and qualitative agreement with the predictions of Cowley (1982). The important dimension brought to these studies by the ground-based observations is the location of the X-line, for which the solar wind parameters can then be used to give first-order (i.e. gas dynamic) predictions of the plasma density and temperature of the magnetosheath at the X line. The effect of features like the plasma depletion layer, not included in the gas-dynamic predictions, may also be studied. A phenomenon which urgently needs explanation is how quasineutrality is maintained, even though the injected electrons move so much faster than injected ions (objective η—see Onsager *et al.*, 1993). The lower density, higher average energy plasma seen on the most-recently reconnected field lines (because of ion flight time effects) is almost certainly what is called the "cleft/LLBL" precipitation (Newell *et al.*, 1989; Newell and Meng, 1992). It is a question of recent debate as to whether there is also an LLBL on closed field lines (Onsager *et al.*, 1995) and, if so, where it is, how it is populated with sheath plasma and what voltage this mass transfer places across such a closed LLBL. The existence, occurrence, thickness and voltage of a closed LLBL can be evaluated by looking for LLBL-like precipitation on field lines whose motion and evolution, as seen by the radars, cannot be explained as newly-opened field lines (Newell *et al.*, 1991; Nishida *et al.*, 1993) (objectives θ and λ). In addition, "double" or "overlapping" injections have been seen in the higher density "cusp" precipitation (Norberg *et al.*, 1994). These pose interesting and challenging theoretical problems in terms of understanding how these particles are injected across the magnetosphere onto field lines which are convecting but are then dispersed according to their time-of flight, such that two distinct populations are seen at one observation time (objectives Ξ and Ω).

Pulses of reconnection, between the geomagnetic field and an IMF with a large B_y component, have been invoked as a cause of transient flow bursts and coincident poleward-moving transient auroral events in the cusp/cleft ionosphere (Sandholt *et al.*, 1985, 1990; Lockwood *et al.* 1989, 1993b; Pinnock *et al.*, 1993). A key question about the predominantly red-line (630 nm) auroral events is the altitude at which they are produced, as this influences our estimates of the size of the events (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 have been shown to be coincident with the upward field-aligned current of the oppositely directed matched pair which transmit the longitudinal motion into the ionosphere, in some cases at least (Sandholt *et al.*, 1990; Lockwood *et al.*, 1993b). However, the causes of the required electron acceleration are not known. The ESR will be ideal for studying these processes and the emission profiles. 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 (objectives μ, ξ—see Lockwood *et al.*, 1993b). The pulsed nature of reconnection has been invoked in a variety of ways as a part of suggested mechanisms for the production of polar cap density patches (e.g. Rodger *et al.*, 1994a). These hypotheses could be tested if EISCAT/ESR were used to detect the patches and monitor their formation, while the Cluster observations of the cusp ion dispersion characteristics were used to evaluate the reconnection behaviour (objective Σ). The flow bursts observed by EISCAT must be associated with transient enhancements of dayside field-aligned currents but the temporal evolution of the distribution of dayside field-aligned current caused by reconnection pulses have not yet been studied (objective Δ).

A major complication is 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, propagation and lifetime of TCVs are 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 any of the current theories of their generation (objectives Λ and σ).

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 cause only smoothed poleward flow unless the magnetosheath B_y component is large (see review by Lockwood 1995a). Comparisons between EISCAT/ESR and Cluster, 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 (objective A). 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 (objectives J and G).

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 ESR radar 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-EISCAT/ESR data can yield information about the location and causes of the cleft ion fountain (objective τ).

4. An Operations Scenario

At the time of writing, the exact Cluster orbit period is unknown and hence neither are the date nor UT at which the spacecraft are in any one location. As it is the UT which determines the location of a ground-based facility, this information is vital for planning coordinated measurements with EISCAT/ESR. Consequently, detailed plans 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 3 considers the evolution of the relative locations of the satellites and ESR, following an ideal occurrence of just one configuration (the example chosen here is number 5) from the list given in Table 1. This conjunction is said to be ideal if the satellites are at noon when crossing the dayside auroral oval, and EISCAT/ESR is also at magnetic noon (which is at a UT of roughly 9 hrs at Svalbard). This can be seen to be the case for orbit I because the difference in MLT 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 $\delta L = 9$ hrs. For orbit 3, δL is –6 hrs when Cluster is in the interior cusp. Note that although this is not a usable occurrence of the (very high priority) configuration 5, satellite data on the cusp could still be of use because it is an ideal occurrence of configuration 8 (high priority).

Table 3.

Orbit number	Day number	UT (hrs)	MLT difference of GB station from satellite ΔL (hrs)	Deviation of satellite MLT from ideal, δMLT (hrs)
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

Orbit 5 gives a configuration 3 when Cluster is in the interior cusp but, as shown by Table 1, this is considered a low priority. The interior cusp crossing on orbit 7 yields configuration 12 (high priority) and 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). If, for example, we wish the satellite to be within 2 hours of the ideal ($|\delta MLT| < 2$ hours) for any one configuration, we will only have 2 or 3 occurrences per year of the mission. Note that the planning pages allow the user to specify the maximum $|\delta MLT|$ and $|\delta L|$ which are acceptable.

A corresponding analysis can be applied to each of the configurations/conjunctions which occur with Cluster at other points of the 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 requires Tromso at 24 MLT, so that the satellites are at apogee in the tail at about 21:30 UT. This is roughly achieved during orbit 2 in Table 3 on day 4 at 23:30 UT (so $\delta L = 2$ hrs) and during orbit 7 on day 16 at 20:30 UT ($\delta L = -1$ hr). Other important configurations will also occur in the same period. The complexity of the planning is yet further increased by the choices for operations made by the Cluster SWT, their selection of high resolution data gathering periods, satellite separation strategy and the instrument modes.

The World-Wide Web (WWW) pages compile for the user a list of the predicted occurrences, for a user-specified ground-based observatory, of one or more of the configurations, to within a $|\delta L|$ and $|\delta MLT|$ tolerance which is also set by the user.

5. Conclusions

We have outlined a procedure whereby ground-based observations by the EISCAT and ESR radars (and all other ground-based observatories) can be planned so as to support the Cluster mission to maximum effect. We have also briefly reviewed some past combined satellite and ground observations and suggested objectives to stimulate thinking about the variety of measurements which could be carried out. 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. It should be noted that Table 1 contains many examples which do not rely on magnetic conjugacy between the satellites and the ground observatory.

The planning is not only required for the operation of the ground-based observations, because it is also vital that we are able to input the wishes of the ground-based community into the Cluster operations planning cycle at the earliest possible opportunity. The World Wide Web pages (URL: http://wdcc1b.bnsc.rl.ac.uk/) provide a simple way for the community to view current orbit predictions and operational plans and to input their own wishes. We urge all users and operators of ground-based facilities to familiarise themselves with them in advance of the Cluster launch.

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