The Case for Swedish EISCAT Research beyond 2006

by Stephan Buchert, Thomas Leyser
Swedish Institute of Space Physics, Uppsala

Asta Pellinen-Wannberg, Evgenia Belova, and Sheila Kirkwood
Swedish Institute of Space Physics, Kiruna

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To the Swedish Research Council

Contents

1 Executive Summary

This document presents the scientific case for continuing the EISCAT Scientific Association and for renewing its facilities. We show that Swedish EISCAT research delivers internationally highly regarded results, has been multi- and interdisciplinary, increased our knowledge in several areas of physics, and has been relevant for the needs of the society.

Goals of future EISCAT related research in Sweden are outlined. They are ambitious yet realistic, and require the continued and increasing operation of the EISCAT facilities as well as their renewal. They aim at

- studying short and long term effects of external perturbations on the near-Earth space environment, such as the influence of solar activity, meteoroids and extraterrestrial dust, to increase knowledge of solar system physics and space weather;
- studying short and long term effects of internal perturbations on the atmosphere and ionosphere, such as the influence of atmospheric electricity and anthropogenic effects, to contribute to the knowledge of global change;
- investigating the dynamics intrinsic to geospace, including magnetic storms and substorms, as well as atmospheric phenomena, to understand the complex multiple scale processes in geospace;
- investigating spatial and temporal self-organisation in plasma turbulence, to increase fundamental knowledge of the response of plasma to energy flows and insight into open nonlinear systems.

These goals span the whole range from basic research, seeking to understand the complex and dynamic space environment of the Earth, to applications related with space weather, for positioning/navigation systems, and for new space-based technologies such as energy transfer via microwaves. In addition, the EISCAT facilities are of great value for technical and scientific education in Sweden.

It is proposed that Sweden remains an active and leading member of the EISCAT Scientific Association, and that the Swedish Research Council together with other Associates establishes an agreement for continuing the Association after the year 2006 for at least one more solar cycle. The observation time and resources requested by users of EISCAT in Sweden will, following the present trend, increase over the coming years.

We also suggest, in consensus with an international community of EISCAT users, that a new multi-static phased-array VHF radar be planned and constructed with capabilities that are not found presently at EISCAT or comparable projects. These new capabilities include the possibility to receive the transmitted signal remotely simultaneously from several and from adaptive common volumes in space, to switch rapidly the directions of transmitted pulses, to perform directional 2-dimensional interferometry for high spatial resolution measurements, and to operate nearly continuously over extended periods of time.

2 Introduction

The EISCAT (European Incoherent Scatter) Scientific Association is an international research organisation that operates some of the world's most advanced scientific tools for ground-based electromagnetic probing of the near-earth space environment. The EISCAT facilities comprise three incoherent scatter radar systems and one powerful radio pump facility in northern Europe. The first agreement to establish and fund EISCAT was signed in 1975 by six European research councils or organisations. In 1995 also Japan joined the Association as the seventh member[1].

Sweden is a founding member of EISCAT. The organisation is established as a "stiftelse", a non-profit foundation governed by Swedish law. EISCAT is the only international research organisation in science with headquarters (HQ) in Sweden. It is located in Kiruna, where one of the EISCAT radar receiver sites is also located.

The Associates are represented in the highest body of the EISCAT organisation, the Council, where all important decisions are made. Associates also send delegates to the Scientific Advisory Committee (SAC) and the Administrative and Finance Committee (AFC). The Rules and Procedures governing the EISCAT Scientific Association are laid down in the EISCAT Blue Book (available from the EISCAT HQ).

Researchers from all Associate countries benefit from EISCAT by having the privilege to operate the radars for their particular research goals. They have an exclusive right to their data for one year. After that these data as well as other EISCAT data are freely accessible worldwide through data centres and data bases on the Internet. The great majority of EISCAT related research gets published in theses, peer-reviewed journals, and books.

The annual budget of the Association is about 32 MSEK. The Swedish share is 9.3 % which is paid by the Swedish Research Council (Vetenskapsrådet). EISCAT uses the annual budget for operating the facilities, maintaining them, as well as for technical development of hardware and software for the benefit of users in the Associate countries. Construction of new facilities, sometimes also major upgrades, generally require investments in addition to the annual budget. The Knut and Alice Wallenberg Foundation financed the Swedish share for the construction of the EISCAT Svalbard Radar (ESR) at a total investment cost of 125 MSEK, approved by the EISCAT Council in 1992 and inaugurated in 1996.

The present agreement between Associates expires at the end of 2006. Among most of the users of EISCAT a consensus is emerging that EISCAT operations should continue well beyond this time in order to achieve a diverse number of science goals. Highly interesting and top quality research could be pursued with the construction of a new "high-tech" EISCAT facility. The process for

[1] The EISCAT Association is supported by Finland (Suomen Akatemia), France (Centre National de la Recherche Scientifique), the Federal Republic of Germany (Max-Planck-Gesellschaft), Norway (Norges Forskningsråd), Sweden (Vetenskapsrådet), the United Kingdom (Particle Physics and Astronomy Research Council) and Japan (National Institute of Polar Research).

establishing a new agreement between the present Associates is in full progress among the EISCAT Council, the Scientific Advisory Committee, users as well as the director and executives. Potential new members have been identified and contacts to the candidate members have been established. New facilities or major upgrades of the existing ones are being studied.

Users of EISCAT with affiliation in Sweden have held a workshop to discuss the future needs and the science case for continued membership, extensions and new facilities after 2006. The workshop took place in Uppsala on 24-25 April 2003, and attracted nearly 30 participants. The Swedish Research Council generously supported our workshop. The workshop clearly demonstrated the diversity in the science pursued by EISCAT users in Sweden (see Appendix I for a the program of the workshop). Several breakthroughs of international impact have recently been achieved. Much of this research is outside of what may be called "genuine" EISCAT research. This development directly contributes to a platform for future creative uses of EISCAT.

This document, based on the fruitful discussions held as well as on input from the many EISCAT users that were contacted, briefly reviews science achievements in the past, and outlines the present status, interest and goals of EISCAT related research in Sweden beyond 2006 in the areas of

- ☞ atmospheric physics,
- ☞ active plasma turbulence and geospace physics,
- ☞ auroral physics,
- ☞ geospace,
- ☞ meteoroid physics,
- ☞ as well as applications.

The interest in EISCAT coming from research performed in Sweden extends over a wide range of scientific and technical topics. In addition, the presence of EISCAT in Kiruna is of strategic relevance for higher education and science research in Northern Sweden. Furthermore, scientists have been driving forces in many satellite-radar collaborations such as with Viking and Cluster. During the last decade, scientists working at the EISCAT HQ in Kiruna have made essential contributions to the design and implementation of new radar hardware and signal processing systems for the ESR and the mainland systems upgrade.

This document shows that the EISCAT facility is of high scientific and strategic importance for Sweden and that the scientific outcome has been and will continue to be on the highest international level. On behalf of the Swedish EISCAT users, we argue that not only the Swedish membership in the EISCAT Association should be continued, but also that Sweden together with other Associates should invest in a new, modern facility for EISCAT.

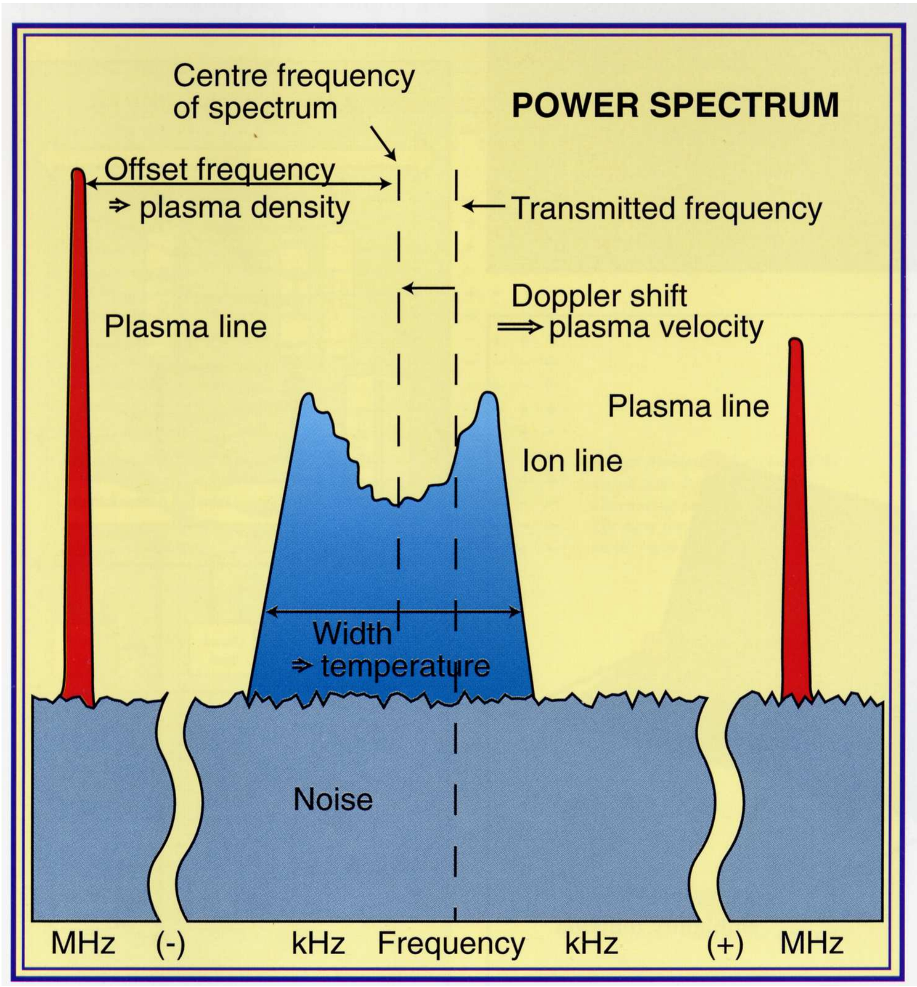

Figure 1: Incoherent scatter spectrum from a collision-less plasma consisting of the ion lines near the centre frequency and plasma lines a few MHz above and below the ion lines. The power and shape of the ion lines as well as the positions of the plasma lines are used to estimate plasma density and velocity, ion and electron temperature, and ion composition (from Jeff Thayer, SRI Intenational).

3 Physics Background

At frequencies below the plasma frequency, typically less than about 5–10 MHz for the Earth's ionosphere, electromagnetic radiation is reflected from a plasma (i. e. a gas containing ions and free electrons). This is how the ionosphere was discovered at the beginning of the 20th century. So-called ionosondes were first developed in 1924 to study the ionosphere systematically (E. V. Appleton, Nobel prize 1947). These instruments transmit radio waves and receive the reflected waves from the Earth's ionosphere.

In the fivties it was recognised that also a much weaker signal, not reflected but quasi-incoherently scattered, is detectable at VHF and UHF frequencies. "Incoherent Scatter" refers to the physical process that scatters electromagnetic waves above the plasma frequency.

Incoherent scattering also denotes that collective, thermal plasma processes are important, making it a very powerful remote sensing tool for plasmas, as it enables us to estimate density, ion and electron temperatures, ion species, collision frequency, and velocities (see Figure 1). Using models or complementing measurements with other instruments we can then derive more parameters related to the electrodynamic coupling of the ionosphere with the space above, the Earth's magnetosphere, and the upper neutral atmosphere (Figure 2).

Laboratory plasmas, particularly in devices for nuclear fusion, are also diagnosed with a technique based on the same process as incoherent scattering, (e. g. Kondoh et al., Rev. Sci. Instr., 72, 1143, 2001). Instead of radars, powerful lasers are employed, and our colleagues prefer to call it (collective) Thomson scattering.

While incoherent scattering has proved to be extremely useful for probing the ionosphere, a high transmitter power ($\sim$ 1MW in pulses), large antenna gain, and sensitive receivers are needed making it a relatively expensive technique, compared to other ground-based instruments, though also one of the most powerful ones. As of today about ten incoherent scatter radars are operated world wide. They have been located either at strategic places adapted to their primary application, such as auroral zone research (EISCAT, ESR, Sondrestrom on Greenland) or along a magnetic meridian (Sondrestrom, Millstone on the US east coast, Arecibo in Puerto Rico, Jicamarca in Peru), as shown in Figure 3. The first to be constructed were Jicamarca and Arecibo in the early 1960s.

The original research goals that one hoped to achieve with EISCAT included studying the ionosphere in the auroral zone, its coupling with the magnetosphere, and measuring the neutral winds in the thermosphere. Great progress has been made in the 22 years of operation from 1982 until now (2004), and some of the goals have been reached (please see Section 5).

Moreover, the EISCAT radars have not only received incoherently scattered signals, but also echoes from the middle atmosphere, from meteor and dust impact onto the atmosphere and from plasma waves. Some of the physics behind the new scattering processes are not yet completely understood, yet these echoes also provide valuable information about the atmosphere, plasma and the meteors themselves.

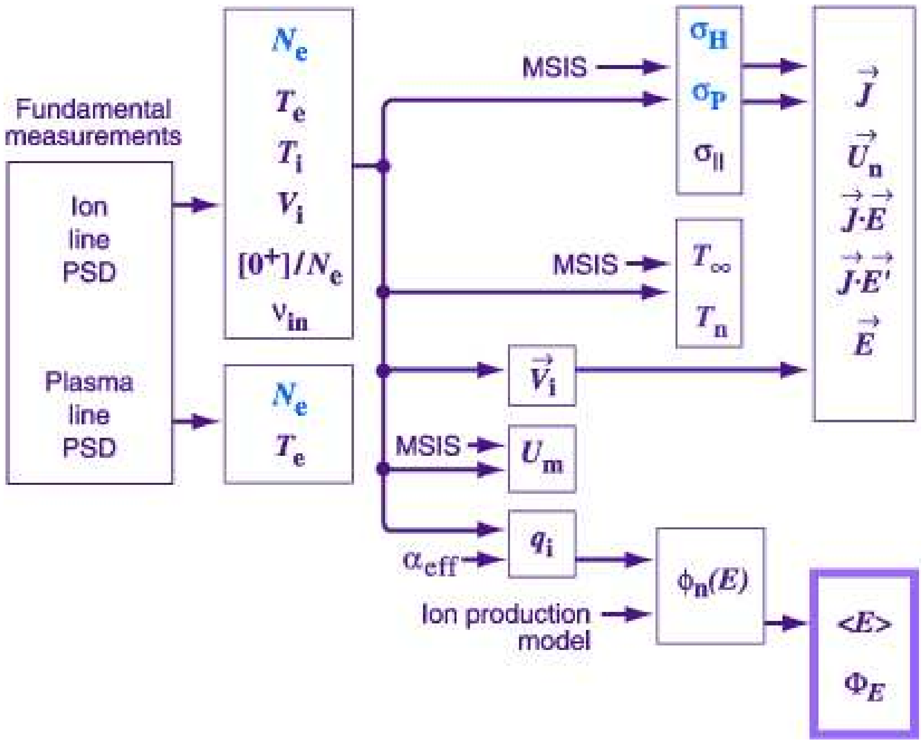

Figure 2: Chart of parameters measured by IS radars. The parameters on the left side of the chart are estimated by fitting the ion and plasma line power spectral densities with incoherent scatter theory, compare with Figure 1. Using a Mass-Spectrometer-Incoherent-Scatter (MSIS) model, the conductivities, thermosphere temperatures, and the neutral wind can also be derived from the directly estimated parameters. This combination of parameters gives information about the parameters on the right side of the chart, particularly regarding the electromagnetic energy transfer between space and the Earth's upper atmosphere.

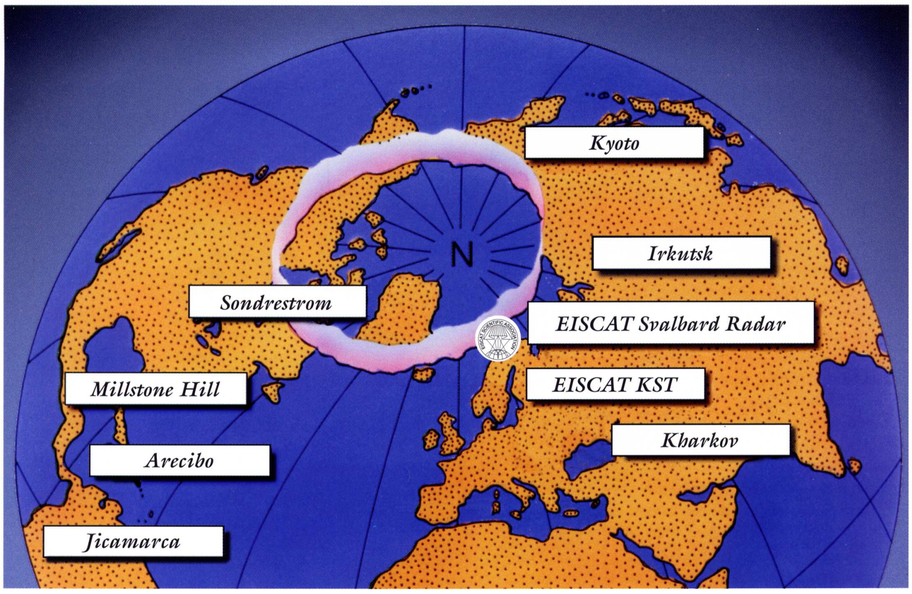

Figure 3: IS radars in the world

Recently the solar wind has been studied with EISCAT by probing regions close to the solar limb with signals arriving from distant quasars. With a new 1.4 GHz option, EISCAT comes closer to the sun than any other current diagnostic tool to study directly the region in which the solar wind is being accelerated, and in which turbulent interaction regions between wind streams of different speed can develop.

To summarise, the community using EISCAT has become broader in scope and found new research goals. EISCAT has extended enormously the spatial region that can be investigated, and also opened a new window towards the small-scale, micro-physical world in the aurora. This has attracted more scientists, students and new member countries. Through its versatility, EISCAT has been the leading instrument in its field. For the moment we can see a new world-wide wave of interest for radar applications. This can partly be explained through the development in signal processing and computational capabilities which allow us to push the radar resolution much closer to its fundamental limits.

4 The EISCAT Scientific Association

4.1 The Organisation

EISCAT was founded in 1975 by the Research Councils, or equivalent, of Finland, France, Germany, Norway, Sweden and United Kingdom. The operations started early in the 1980s with the mainland UHF and VHF radars. Japan

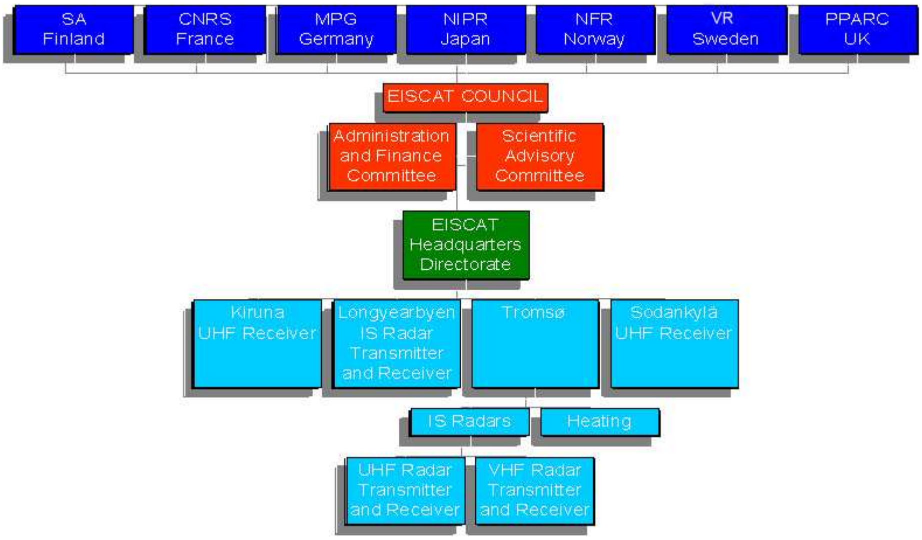

Figure 4: Organisation of the EISCAT Scientific Association

joined the organisation in 1995 when the Association expanded with the ESR. Like other international research organisations EISCAT is governed by a Council. The Council is advised by the SAC (Scientific Advisory Committee) and the AFC (Administrative and Finance Committee). Associates are represented in the Council and send delegates to the committees. The Council can also nominate up to three external members of the SAC for a duration of two years. The organisation is presented in Figure 4. The highest executive at EISCAT is the Director who has her or his office at the HQ located in Kiruna, Sweden. The EISCAT facilities are operated at sites in Norway, Sweden, Finland, and on Svalbard.

The total number of staff administering the Association and operating the sites is about 35. Only staff at headquarters is employed by EISCAT. People working at the sites are employed by national universities and institutes in the host countries Norway (University of Tromsø), Sweden (Swedish Institute of Space Physics), and Finland (University of Oulu), which partially account for the financial contributions from these Associates.

Unlike some other international research organisations, EISCAT rests not on an agreement betweeb governments, but between national research organisations. Formally the Association is established as a “stiftelse”, a non-profit-making foundation governed by Swedish law. The budgetary accounting unit is the Swedish crown (SEK). At least we, the Swedish EISCAT users, feel that administrative overheads are relatively low, and that the organisation is generally very efficient thanks to its framework, its relatively small size, dedicated directors and staff.

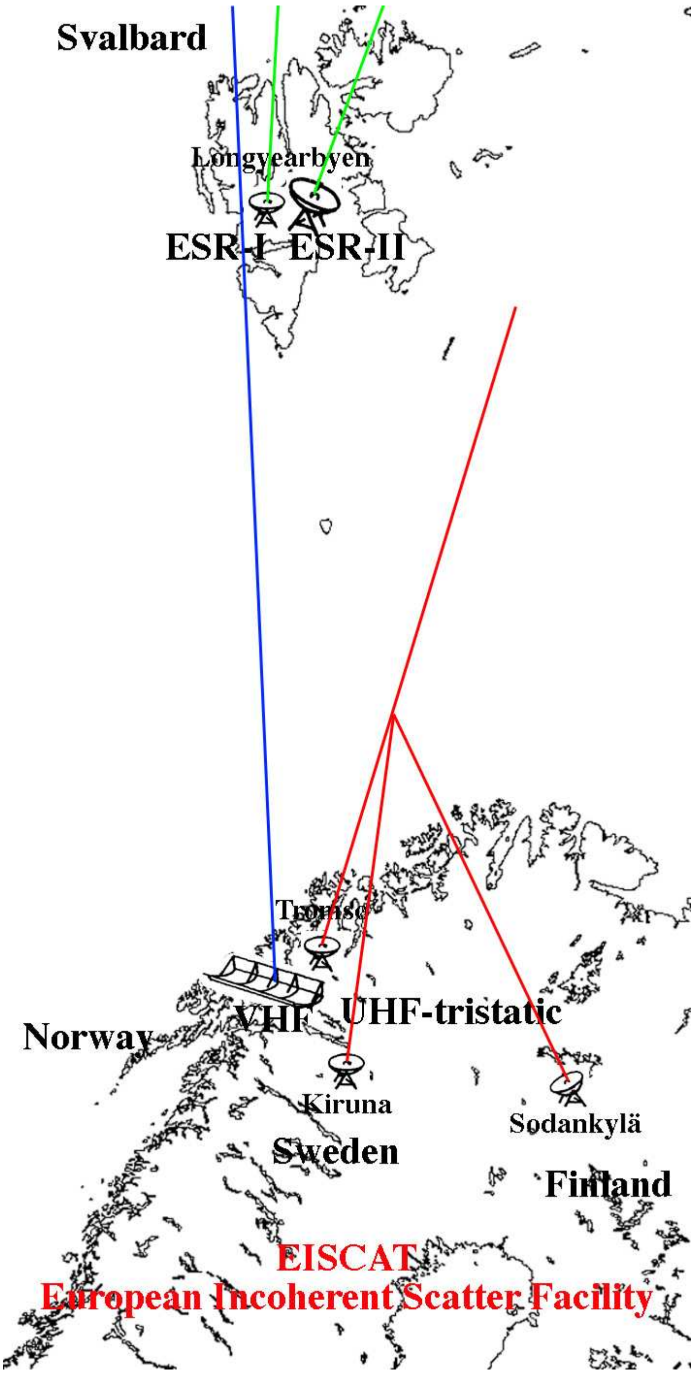

Figure 5: The EISCAT radar sites in Northern Europe.

4.2 The Facilities

The EISCAT facilities comprise three incoherent scatter radar systems and one powerful radio pump facility in northern Europe. The locations of the different sites are shown in Figure 5. Two of the radar transmitters are located in Ramfjordmøen close to Tromsø in Norway. These radars operate at 224 MHz (VHF) and 931 MHz (UHF). The latter system is tristatic with additional receiver stations located in Kiruna, Sweden, and in Sodankylä, Finland. The third radar, the 500 MHz EISCAT Svalbard Radar (ESR), is located near Longyearbyen on the island of Spitsbergen about 1500 km north of mainland Europe. The radar antennas comprise fully steerable 32-m parabolic dishes on each of the four radar sites, a fixed 42-m parabolic dish at the Longyearbyen site and a 40 m x 120 m parabolic cylinder at the Tromsø site. In addition, one of the world's most powerful HF (4-8 MHz) pump facility, EISCAT-Heating for active perturbation of the space plasma, is located at the Ramfjordmøen site. The antennas consist of three square arrays of crossed dipoles, with sides 192 m (5.5–8.0 MHz), 270 m (3.9–5.6 MHz), and 384 m (the Superheater array, 5.5–8.0 MHz).

The EISCAT systems are in good shape considering their age and degree of operation. Both the ESR and the mainland UHF and VHF systems deliver high quality data. Even new operational capabilities have been added recently, such as automatic plasma-line measurements in some radar modes and extended interplanetary scintillation receiving possibilities at 1.4 GHz at the Kiruna and Sodankylä sites. This option will also be installed at the Tromsø site.

The ever-increasing demand for frequencies for personal communications (mobile phones) in the 930 MHz band has caused the EISCAT UHF system major problems over the last decade. In Finland, only 1.5 MHz of the original 30 MHz band now remains available for EISCAT use. In Sweden and Norway the situation is slightly better, but frequencies above 933 MHz are in practise unusable at all three sites.

The VHF frequency assignment around 224 MHz does not suffer the same pressure and it appears that EISCAT will be able to enjoy continued access to it for the foreseeable future. Unfortunately, one of the two VHF transmitter klystrons failed in late 2002 and is still undergoing repair. These tubes were custom-designed for EISCAT almost twenty years ago by a company that has long since left the power tube field. It is extremely unlikely that any tube manufacturer would now undertake to build an identical replacement.

The Heating facility is in satisfactory condition, but could be made much more competitive with very minor upgrades at relatively low cost.

4.3 Operations and Data Access

The facilities operate for 4000 hours per year. One half of the time is dedicated for Common Program (CP) operations. These are run according to a scheme approved by the SAC, for example, to enable investigations based on data gathered over long time spans. The second half is shared between the Associates according to their annual contribution to the organisation. This time is used by individual scientists from the Associate countries to conduct Special Programmes (SPs) suitable for their particular research goals. Conductors of SPs have an exclusive right to their data for one year. Researchers from all Associates have guaranteed access to CP data, and a large fraction of the data is available world-wide through data centres and data bases on the Internet. Also SP data are in practise often made freely accessible.

4.4 EISCAT from the Swedish Perspective

The EISCAT Scientific Association is very important for Sweden. EISCAT is the only international science research organisation with its headquarters in Sweden. In addition, there is a radar site in Kiruna and many active scientists utilising EISCAT at the Swedish Institute of Space Physics (IRF) both in Kiruna and in Uppsala. Occasionally scientists from the Onsala Space Observatory, Royal Institute of Technology, University of Stockholm and Chalmers University of Technology have been involved in EISCAT runs.

At IRF more than 30 researchers have been or are involved in EISCAT related research. On average one doctor's thesis making significant use of EISCAT data has been submitted to Swedish universities per year since 1981. The scientific competence available in Sweden is broad as is the technical expertise concerning hardware, signal processing and coding techniques. The scientific innovations are presented in the following Section 5. In addition, the proximity of the EISCAT HQ and site has also frequently attracted visitors and guest scientists also to IRF.

A total of 11 persons are currently employed at EISCAT HQ and the Kiruna receiver site. All but the Director are Swedish nationals. The three senior positions at HQ (the Deputy Director, the Senior Scientist and the Radar Systems Supervisor), are filled by Swedish scientists after international recruitment processes. The Kiruna site staff has contributed with important engineering and technical efforts to both the ESR project as well as to the mainland radar upgrade.

We can conclude that during its almost 30 years with EISCAT Sweden has developed a high level of competence in the field. In addition, the economical and scientific benefits of having the present EISCAT facilities in Sweden have been significant over the years.

In the future, EISCAT and Swedish EISCAT research should be made more available to the general public. Popular science information on the EISCAT facilities, the diverse research performed with EISCAT, including the complexity of the auroral zone processes, would most likely stimulate interest in the natural sciences in general and in the Swedish participation in EISCAT research in particular.

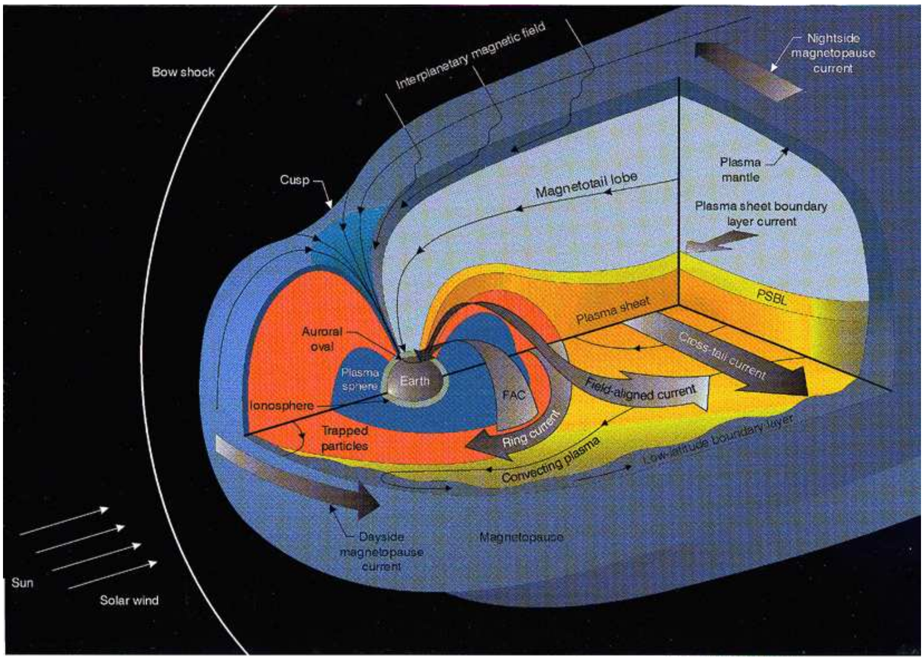

Figure 6: A drawing of geospace and its various regions. The footprint of most of geospace is found in the high-latitude ionosphere where EISCAT is located.

5 EISCAT-Related Research, Past and Future

EISCAT publishes Annual Reports containing highlights of technical developments and also of science results submitted by the Associates. The latest of these reports is available in an extended version at the EISCAT web site, as is a list of all publications where EISCAT data were used (presentlu 1571 of them).

Here we summarise, for different areas of research, highlights of results authors who were or are affiliated to Sweden have published. A list of refereed Swedish publications 1999-present (beginning of 2004) is given in Appendix II. In the period 1990-99 there was an average of 9.5 refereed publications annually, while during the past few years the rate has almost doubled thanks to several exciting new results.

Science objectives for the future are identified. We discuss how EISCAT can be used to achieve those objectives.

5.1 Geospace Physics

5.1.1 Geospace, from basic research to applications

Also called the solar-terrestrial environment, geospace is the domain of Sun-Earth interactions. It consists of the particles, fields, and radiation environment from the Sun to Earth's space plasma environment and upper atmosphere.

Geospace is considered to be the fourth physical geosphere (after solid earth, oceans, and atmosphere). Being a part of the universe, geospace is a subject of mankind's basic research and striving for an understanding of the physical processes going on. Geospace also deserves our attention for many practical reasons, being the surroundings of equipment such as satellites on which our society increasingly depends, as well as being the environment for a handful of astronauts.

Geospace is not closed, external free energy originating from the Sun and transported in the solar wind enters into. This energy is partially dissipated and partially released into the Earth's atmosphere as well as back into the solar wind. One can draw an analogy with the biosphere and the Earth's mantle and crust, where sources of external free energy are solar radiation and heat from the Earth's interior, respectively. In all these systems we witness a self-organisation on a wide range of spatial and temporal scales, as well as the development of a high degree of internal complexity. The challenge for the future is to understanding not only the many aspects and details, but also the overall working of the systems. It involves a multitude of scientific disciplines and tools.

Some of the outstanding features of geospace are as follows. A solar wind hits our planet Earth continuously with varying speed, density and magnetic field. However thanks to the geomagnetic field, solar wind particles do not directly enter the atmosphere, a cavity called the magnetosphere shelters us. The outer boundary of the magnetosphere, the magnetopause, is maintained by processes that are only partially understood. Downstream, on the night side, a huge magnetotail, part of the magnetosphere, extends beyond the moon's orbit. Here energy and particles are stored until they are released in violent events called substorms which are associated with visible outbreaks of the aurora. The Northern and Southern Lights are created relatively close to the Earth ($\sim$ 5000 km altitude) where acceleration of the auroral particles takes place and spectacularly visible structures form. Just before a substorm they are often surprisingly stable and quiet, yet intense. After decades of basic research with ground-based instruments and in-situ observations, progress has been made. However we are still unable to give full answers to some simple questions that witnesses of the aurora might have: why are discrete, quiet auroral arcs so long (several thousand kilometres) and thin (sometimes as narrow as a few tens of meters)? What exactly causes the expansion of a substorm, of an auroral intensification? Why does the typical surge develop and travel westwards along the auroral oval? Even on an "advanced" level, in the specialised scientific literature, models and theories of substorms remain one of the most debated issues. This and the aurora are perhaps the most difficult and unruly subjects of basic research in the field, but by no means the only ones.

Thanks to global efforts our knowledge of geospace is increasing, and it becomes also increasingly the basis for applications. Our expertise on the solar terrestrial environment flows into the design of space craft and their on-board equipment. Space weather, a popular name for energy-releasing phenomena in the magnetosphere associated with magnetic storms, substorms and shocks travelling in the solar wind, is becoming a subject of public and private services similar to the meteorological weather. The users of such services are, for example, spacecraft operators, and providers of communication, constructors and maintainers of power- and pipelines in countries at high geographic latitudes, and interested private persons like aurora watchers and radio amateurs. The Northern Lights attract tourists into remote areas. For example, in the commune of Kiruna, tourism related to aurora and space activity related is becoming increasingly significant as an economic resource.

In summary, after decades of space research our basic understanding of the solar terrestrial environment has increased enormously and revealed a system of perhaps unexpected complexity and richness. However this knowledge is still full of gaps that need to be filled. Needed is new thinking, techniques and observations covering more in space and time, and of new quality. Practical applications, space weather, space-based navigation and education require advanced observing and monitoring tools also in the future.

In the following sections we summarise how scientists, focusing on those affiliated in Sweden, have made essential contributions to the proliferation of our knowledge of the solar terrestrial environment by using incoherent scatter radars, particularly EISCAT. We lay out research goals for the future that are important for our understanding of the solar terrestrial environment and relevant in practice for a society that is expanding its environment into space. The availability of an advanced remote sensing facility like a future EISCAT is necessary for reaching these goals.

5.1.2 The Day-side

The Earth's ionosphere at high latitudes is the lower boundary for a large fraction of all geospace, due to the dipole topology of the geomagnetic field (Figure 6). Both the large-scale plasma convection in the magnetosphere as well as boundaries separating regions in space with different particle populations and the motions of these boundaries are mapped onto the ionosphere. Thus, by sensing densities, temperatures, and velocities in the ionosphere, we also obtain valuable information about the magnetosphere. Observations with sufficient temporal and spatial coverage are needed for the basic understanding of the solar wind-magnetosphere-upper atmosphere system, and for comparisons with models and simulations, e. g. for space weather applications.

It has become clear from numerous studies involving many in-situ and ground-based measurements, that on the day-side the magnetosphere reacts rather directly to changes in solar wind parameters, most importantly to variations in the interplanetary magnetic field (IMF). In the eighties British colleagues were leading studies where the AMPTE UKS satellite and a far-north-looking EISCAT radar recorded one of the first pieces of evidence for a clear, time-delayed response of the high latitude convection after changes in the solar wind (Rishbeth et al., Nature, 318, 451-452, 1985). For many researchers these findings were not unexpected, supporting the concept that merging of the IMF and the geomagnetic field, generally also called magnetic reconnection, plays a dominant role in the solar wind-magnetosphere interaction. Subsequently the four-satellite Cluster mission, the EISCAT Svalbard radar and other projects were designed for the investigation of how the solar wind forces the Earth's magnetosphere,

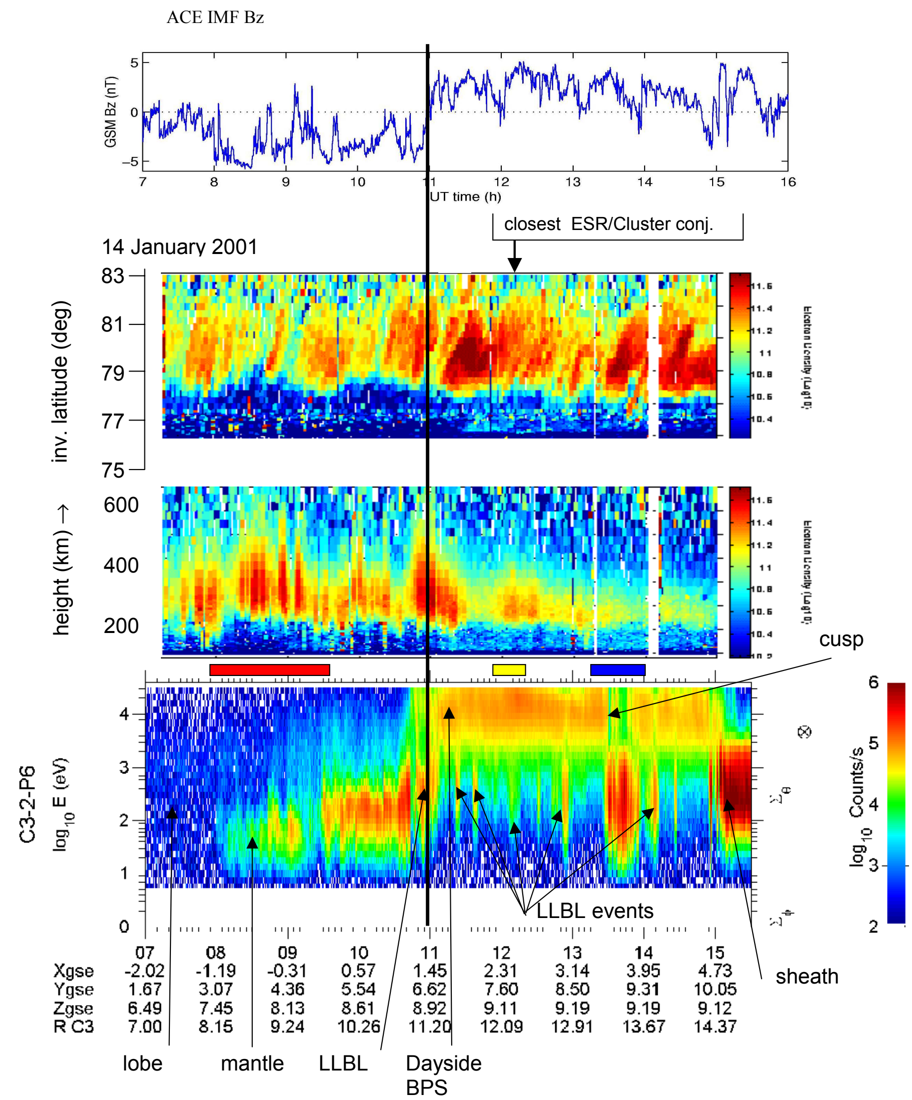

Figure 7: Data from the ACE satellite in the solar wind (top panel), from the ESR radar (middle panels), and from the Cluster Ion Spectrometry, showing how the cusp responds to changes in the solar wind, and the effects of this in the ionosphere.

and these projects are now bearing fruit [1, 2]. For an example see also Figure 7. Presently addressed questions are: exactly where, when, and at what rates is magnetic merging occurring, how competitive are other processes etc? The Cluster satellites are excellent tools for studying local processes which are important for understanding the plasma physics. However we need also to determine, which of the locally studied events are effective on larger scales, globally, and, if they are, in what way. In order to reach this goal high-quality ionospheric measurements need to be considered.

Operation of Cluster and the ESR is planned at least until the year 2006, and we expect a significantly improved basic understanding of day-side dynamics after having looked at the large amount of data that are presently being gathered. Once our basic understanding of the physical processes is sufficiently complete, the ESR together with other instruments monitoring the crucial regions on the day-side will be a powerful tool for space weather and other practical purposes.

5.1.3 Polar wind and ion upflow

Investigation of the polar wind, a quasi-steady outflow of ions from the ionosphere, mainly H^+, along magnetic field lines into space, was one of the prime research goals when the first EISCAT facilities were constructed. Rather than a polar wind EISCAT has observed intermittent, localised upflow of O^+, but from much lower altitudes than originally anticipated [3, 4]. With instruments on satellites even molecular ions, which under quiet conditions occur only in the lower part of the F region, were detected at several thousand kilometres altitude when geomagnetic activity was particularly high. This is consistent with the low altitude upflow seen by IS radars. With the ESR, ionospheric upflow under the so-called cleft ion fountain near and in the cusp on the day-side could be studied, see section 5.1.2. Ion upflow is a first step in a chain of processes putting considerable amounts of mass into the magnetosphere.

For investigating the upflow (to answer whether at high altitudes it becomes supersonic or stays subsonic, to determine its composition, molecular, atomic oxygen, or hydrogen) the sheer power of the EISCAT radars needs to be increased, by having large transmitters and high gain antennas.

5.1.4 A planet without a magnetic field?

A part of the Earth's ionosphere, namely the footprints of the cusps near the northern and southern poles, is frequently in contact with hot and dense solar wind plasma (see also Figure 6). This is a natural consequence of magnetic merging. With the ESR we have been able to see the direct effects of fresh magnetosheath plasma precipitating onto the F region: large increases of electron and ion densities and temperatures, plasma wave activity, and up- and downflow of ionospheric ions [5, 6, 7]. Less direct effects such as changes of the plasma and gas densities and compositions in the ionosphere and upper neutral atmosphere, heat input and wind generation, might well occur, too, and this

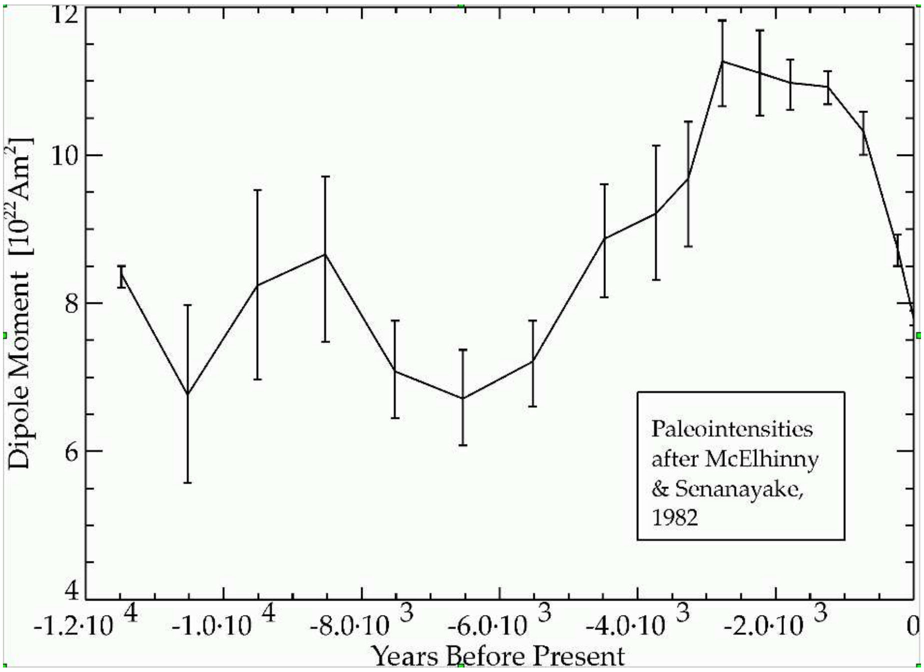

Figure 8: Geomagnetic dipole moment over the last 12000 years estimated from paleomagnetic records

has not been investigated fully so far. Data extending over significantly more than one solar cycle (11 years) are needed, but the ESR with two antennas has only been available since 1996.

When the geomagnetic field changes its polarity and is therefore considerably weakened, large regions of the ionosphere will be impacted by the solar wind. Following the present trend of the Earth's magnetic dipole strength, a polarity change may happen in roughly 1000 years (Figure 8). Presently it is not well understood what consequences such polarity changes had many thousands of years ago, and what mankind sooner or later will experience as a result of a future polarity change. There is evidence that the Sun's magnetic activity also changes over time scales much longer than a solar cycle (Lockwood et al., Nature, 399, 437-439, 1999).

The best empirical study object that can help us to anticipate whether and how variations of the planetary and solar dynamos influence the solar terrestrial environment is the cusp ionosphere of today. In order to get suitable data sets we suggest operating the ESR not only over 1–2 solar cycles, but over at least several decades.

5.1.5 Energy conversion and momentum transfer

Incoherent scatter radars are able to measure parameters related to energy transport and conversion that no other ground-based instrument can provide (compare Figure 2). Conductivities and electric fields are crucial parameters for estimating the electromagnetic energy input from the magnetosphere. From density measurements one can estimate flux and energy of auroral electron precipitation [8, 9, 10, 11, 12], and temperatures indicate how much thermal energy is generated. Extremely high ion temperatures are occasionally observed in the F-region in connection with very large electric fields [13], but dissipative currents in the E region are the largest contributor to energy input into the upper atmosphere [14].

Electron temperature enhancements in the E-region (due to a plasma instability also caused by large electric fields) were already seen with the Chatanika incoherent scatter radar (now at Sondrestrømfjord, Greenland). With EISCAT these were studied further, and the ERRRIS (E-region Rocket/Radar Instability Study) rocket launched from the Esrange facility provided in-situ measurements of waves and particles. The need to observe the E- and also D-regions with improved height resolution has led to the development of new radar codes which can also be used by other types of radars. The so-called alternating codes were proposed by Finnish scientists, and then practically implemented for the Swedish ERRRIS [15]. Today they are used in almost all routine observations with EISCAT, allowing us to study, for example, sporadic E. These are thin (a few kilometres) layers caused by converging flow driven by magnetospheric electric fields [16].

Studies on the basis of a larger amounts of data of the electromagnetic energy transport and conversion in the ionosphere have been done (Fujii et al., J. Geophys. Res., 104, 2357–2365, 1999). The role of winds in the thermosphere taking up momentum and transporting it away from the auroral zone is uncertain, but this is relevant and occasionally can even reverse energy conversion turning the upper atmosphere into a dynamo for the near-Earth space (fly wheel effect). With the presently available tristatic EISCAT UHF radar we can uniquely determine the velocity vector, but only at one altitude on one magnetic flux tube, which is not enough to estimate the energy input over some area.

Reception of the transmitted signal remotely over a range of altitudes and the rapid or, under favourable conditions, simultaneous forming of transmitter beams in different directions is needed in order to remove these limitations and assess the auroral energy input and momentum transfer into the thermosphere more thoroughly than is possible at present.

5.1.6 Substorms and other geomagnetic disturbances

The Swedish satellite programme, in addition to rockets launched from the facilities at Esrange, Sweden, and Andøya, Norway, provided opportunities for coordinated observations of auroral phenomena from space and on the ground. Auroral substorms in their different phases were investigated particularly with the Viking satellite and EISCAT [17, 18]. The Aureld-VIP sounding rocket was launched from Esrange to the Viking satellite footprint during a strong geomagnetic disturbance [19, 20]. Also a relatively globally distributed set of ground-based instruments including EISCAT enabled us to investigate how regions are effected that are clearly separated from a substorm current wedge located on the night-side [21]. These multi-instrument studies have helped us to establish the phenomenology of geomagnetic disturbances, most prominently of substorms, in space and unprecedented in detail. Typical values of parameters, for example of current densities, conductivity enhancements, and acceleration potentials, could be determined quantitatively. Especially the importance of ionospheric conductivity variations in the coupling between ionosphere and magnetosphere could be shown.

As already stated at the beginning of 5.1.1, however, the phenomenology of substorms in many respects still lacks physical explanations and identification of causes and effects. Our colleagues in North America recognise this in particular: NASA will launch multi-satellite missions aimed at solving these questions. In this context NASA also funds upgrades of ground-based instrumentation in the North American sector (see the brief descriptions of the THEMIS, NorthStar, and MMS projects in section 6).

Geomagnetic disturbances like substorms are ultimately caused by the solar wind, but due to reservoirs of energy and mass inside the magnetosphere a system develops with complex internal structure and dynamics which is only fragmentarily understood even today. A better understanding can only result from a global network of advanced instruments located both on the ground and in space. Incoherent scatter radars provide us locally with invaluable data and need to be available also in the future within this network.

5.1.7 Aurora and Small-Scale Structures

With help of today's advanced optical instruments (see section 6.3.5 it has been shown that auroral structures are found even at the smallest scales near the fundamental physical limits (e. g. the electron gyro-radius). Data with a very high time resolution were available with instruments on for example the FREJA and FAST satellites. Also EISCAT measurements have been pushed to time resolutions well below one second. These observations have revealed, that small scale electric field variations with very large amplitudes occur even at ionospheric heights in the F region and a few hundred kilometres above. There is a large number of models and theories for the aurora, 21 of them were reviewed in 1993, and since then more were published (Borovsky, J. Geophys. Res., 1993). Clearly, more empirical research is needed in order to understand how the aurora and its internal structure and motions are generated.

EISCAT has already contributed pieces to the solution of the auroral puzzle, for example with the discovery of so-called naturally-enhanced ion-acoustic lines, but it is uncertain where this piece belongs in the puzzle. Recently a way has been found to perform directional interferometry with the two antennas on Svalbard, and the ion-acoustic lines seem to originate from areas considerably smaller than the antenna beam width and comparable in size to optically-recorded auroral structures (Grydeland et al., GRL, 2003).

Interferometry opens the small-scale world of the Northern Lights for the powerful incoherent scatter radar. However the interferometric observations with the presently-available EISCAT facilities suffer from severe limitations, since only the two antennas/receivers on Svalbard can be used. We need to perform 2-dimensional interferometry (with more than two antennas/receivers), together with complementing instruments like the optical ALIS (see section 6) and on-board sounding rockets in order to achieve substantial progress in the study of the auroral plasma and other phenomena involving spatial structuring at small scales.

Tomographic inversion of optical measurements of aurora has been done first with relocatable CCD cameras deployed near EISCAT (Frey et al., Ann. Geophys., 16, 1332–1342, 1998). It is presently the most powerful technique to resolve 3-D structures and their motions of the aurora and of artificial airglow on medium scales. Radar measurements of densities, temperatures and plasma motion ideally complement this technique and the combination of both optical and radar data allow us to understand much better the physics of aurora and airglow. Again, the limition of the present EISCAT, that there is a velocity vector from only one common volume, needs ot be removed in order to make significant progress.

5.1.8 Active geospace physics

Here we discuss ground-based research which utilises the EISCAT-Heating facility to transmit a powerful HF (high frequency) electromagnetic wave into the ionosphere to study the geospace environment. In these active experiments the Heating facility is used to research natural processes in near-earth space by stimulus–response experiments. When studying a natural system, for example a mouse, it is common to first simply observe its behaviour. This observing phase might involve waiting for the mouse to appear, trying to notice conditions for its appearance, and generally watching it once it appears. At some level of understanding our curiosity often drives us to interact weakly with the system under study, seeking to answer questions like what kind of food the mouse prefers, if it has a choice, or how intelligent the mouse is. Similarly, active stimulus–response experiments using powerful radio waves can help us to increase our understanding of natural processes in geospace. Powerful radio waves can be used to derive parameter values of the ionosphere and upper atmosphere (mesosphere and thermosphere), which are not easily accessible by other means. For example, measurements of the radiative life-time of pump-induced optical emissions have been used together with modelling to give altitude profiles of molecular oxygen and nitrogen in the thermosphere. Further, HF pumping can be used to visualise geospace phenomena, to investigate geospace phenomena by stimulus–response experiments, and to interact with free (natural) energy sources in space such as aurora. These uses of HF pumping are likely to become of increasing importance in future research using EISCAT. Such active experiments complement and expand on the commonly-used more passive observations of naturally-induced phenomena in geospace with the incoherent scatter radars and other observing tools alone.

As mentioned above, when first studying a complex system one usually simply observes the system. It is then natural that, if possible, this initial observing phase is followed by a phase of weak interaction with the system in which a controlled perturbation is applied and the system's response is observed. Such stimulus–response experiments using powerful radio waves to stimulate different phenomena in geospace to investigate their properties are becoming of increasing importance. A beautiful example of a stimulus–response experiment is the modulation of PMSE layers recently performed by Swedish researchers using EISCAT [22, 23]. There are of course also other thin ionospheric layers to be studied in the future with this technique, including sporadic E layers, the sudden Sodium layer, and meteor trails. Another most interesting research topic is to attempt modification of the ionospheric conductivity during auroral conditions. In 2003 experiments were performed to modulate the ionospheric conductivity by pump-induced heating in the vicinity of quiet auroral arcs. Measurements were made with a number of different instruments, including the UHF and VHF radars as well as ALIS for optical imaging. At the time of writing the data has not been analysed so that the auroral response to the stimulus is not yet known. The long scientific work of passively observing the aurora is thus now complemented by a new phase in which controlled interaction with auroral processes is being attempted. These are just the first experiments which therefore need to be developed in the coming decade. Whereas such stimulus–response experiments are difficult to perform, since the right auroral and atmospheric conditions must be present at the time of the experiments, a successful experiment give most useful information. Such active experiments also allow us to interact more directly with modelling and its predictions, which of course gives a fruitful scientific situation.

New types of experiments have been suggested in order to explore the interaction of powerful radio waves with free energy sources in the near-earth space environment. In laboratory plasma, electron beams are commonly used to excite plasma turbulence. In high latitude geospace, precipitating auroral electrons and ions provide free energy for the growth of plasma turbulence. Interaction of the energetic electrons and HF pump-stimulated Langmuir waves may lead to a channelling of free energy into the excited waves. Such pump-induced channelling of the energy of auroral electrons may open up new regimes for ionospheric plasma research, both with respect to induced local modifications of the ionospheric conductivity to explore ionospheric physics as well as larger scale Langmuir turbulence effects to study strongly nonlinear plasma turbulence.

Interaction of the energetic electronsand HF pump-stimulated Langmuir waves may lead to a channeling offree energy into the excited waves. Such pump-induced channeling of the energy of auroral electrons may open up new regimes for ionospheric plasma research, both what concerns induced local modifications of the ionospheric conductivity to explore ionospheric physics as well as larger scale Langmuirturbulence effects to study strongly nonlinear plasma turbulence. The very first cases of such seeding of pump-induced Langmuir turbulence channeling the auroral electron energy into the turbulence appears to have been achieved in experiments in November 2003 as observed with the VHF radar (by Belyey, Isham, Leyser, and Rietveld).

The feedback in the ionosphere–magnetosphere system will be investigated by pump-induced conductivity perturbations in the lower ionosphere during auroral conditions. With such perturbations Alfvén pulses can be excited and the concept of, for example, the ionospheric Alfvén resonator can be tested experimentally. Initial results have been obtained with EISCAT which suggest the possibility of pump-triggering of local auroral activation [24]. Moreover, it has become clear that substorms may occur without an identifiable external trigger, which indicates a trigger internal to the magnetosphere. But can a local perturbation in the ionospheric conductivity, induced by a powerful radio wave, feed back into the magnetosphere and during certain specific conditions actually trigger the large-scale dynamics of substorm related processes? Answers to such questions give important information on geospace and also related to space weather. However the difficulty and complexity of such experiments probably requires a research programme extending a few decades into the future.

Stimulus–response type of experiments using powerful HF waves transmitted from the Heating facility to interact with different phenomena in the ionosphere and magnetosphere are likely to become of increasing importance in future EISCAT research. These active experiments complement and expand on observations of naturally induced phenomena. It is essential for such experiments to transmit the highest possible HF power in order to achieve an effective stimulation of the space plasma process under study. It is therefore desirable that the maximum effective radiated power of the Heating facility is significantly increased.

5.2 Atmospheric Physics

Atmospheric physics is an extended part of geophysics. It covers the whole altitude region from the Earth's surface up to the exosphere (the region above 500 km where atmospheric molecules can leave the denser atmosphere and move out into space). Atmospheric physics deals with many different subjects such as atmospheric dynamics and thermodynamics, atmospheric chemistry, radiation and clouds and many others. The atmosphere is part of the environment which allows human beings to live on planet Earth. Scientists study the atmosphere because it is most important to understand how it works and how it might be changed by human activity.

Radars of several different types are widely used in atmospheric research: precipitation, weather, MST, meteor radars. They measure basic atmospheric parameters that can be further used e.g. as input data for atmospheric prognostic modelling or for long-term monitoring of the atmosphere. The latter is an important aspect of atmospheric research. It is closely related to climate change issues, the foremost "hot" topic at this stage in human history. Our present and future climate on the Earth is affected not only by anthropogenic factors, but also by natural variations. To estimate the human contribution to global change the collection of climatological information (e.g. seasonal, tidal, solar cycle variations) and especially the monitoring of global change indicators, is a necessity. This requires measurements over time periods longer than natural cycles. Moreover, to collect long time series of atmospheric measurements including many which are not of immediate interest to today's already identified, environmental problems, is of prime importance if we are to discover unexpected changes.

Several atmospheric parameters such as neutral temperature, density and winds can be derived from EISCAT radar basic measurements. Winds are also measured using other radars such as MST, MF and meteor radar, and temperatures can be measured by lidars, from optical emissions and, to a certain extent, from meteor radar. However the EISCAT radars are the only ones which measure all parameters all the year round for the altitude region 90–110 km. The EISCAT radars also have distinct advantages over other radars when electron densities are enhanced e. g. due to solar proton events.

There have been studies made of seasonal and solar cycle effects on lower thermosphere parameters using long-term observations with EISCAT [25, 26]. Results have contributed to considerable improvements of the main empirical model used by the community. They have also shown both direct solar radiative effects and evidence for circulation changes following the solar cycle. Another solar cycle of EISCAT observations will be completed in 2004 and it may then be possible also to look for any longer-term trends. ESR observations will soon cover one whole solar-cycle, allowing differences due to geographical location to be assessed.

However, it must be realised that most processes in the thermosphere (above 90 km) and even in the middle atmosphere (above 20 km) which are likely to be affected directly by the most variable parts of the Sun's radiation are not of major importance for the atmospheric conditions at the Earth's surface i. e. for weather and climate. There is some evidence that dynamic changes introduced to atmospheric conditions at middle-atmosphere levels can propagate downward and influence climate, but this is still not well understood. In this field, interest is primarily focused on stratosphere (15–35 km) - troposphere (0–15 km) exchange studies, which has been recognised as a challenging topic by the leading scientists of the World Climate Research Programme.

Thus, there are good possibilities for EISCAT in future to contribute to further atmospheric dynamics studies if low altitude (15–60 km) capabilities can be introduced. This would allow the stratosphere to be studied by radar - something which is not possible with the other, less powerful radars available. Furthermore, EISCAT could make a significant contribution to understanding whether/how atmospheric disturbances related to quasi-stationary planetary waves can propagate from high altitudes (50-100 km) down to the troposphere. This can be achieved if regular observations with EISCAT are made simultaneously with an IS radar in Alaska or in Arctic Canada.

EISCAT radars have also been used for observations of thin layers in the vicinity of the mesopause. The highly-enhanced radar backscatters from such layers are known as Polar Mesosphere Summer Echoes (PMSE). PMSE were detected for the first time more than 20 years ago (Ecklund and Balsley, J. Geophys. Res., 86, 7775-7780, 1981) but they are still not completely understood. PMSE represent a complicated coupling between neutral atmospheric components and dusty plasma. Thus, PMSE study can be considered as fundamental physics research. On the other hand, PMSE are closely connected to atmospheric waves and aerosols, and can be used to study middle atmosphere dynamics including

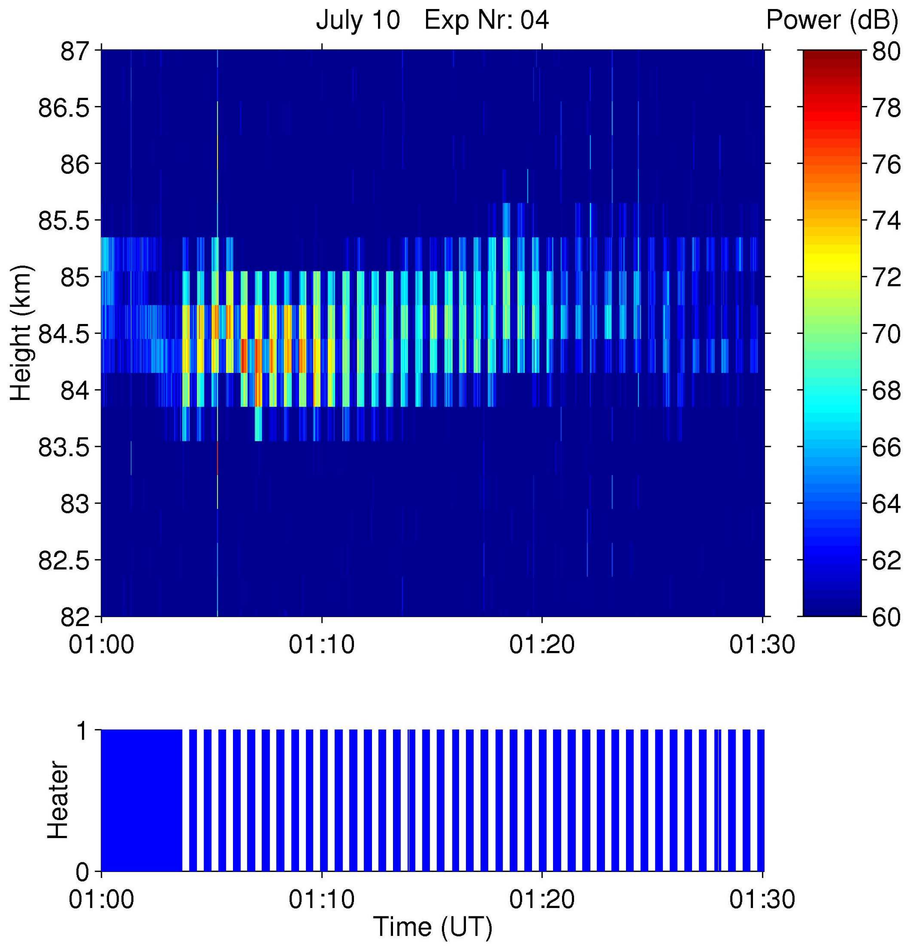

Figure 9: PMSE powers during heating experiment on July 10, 1999are shown in the upper panel. The lower panel shows the state of the heater where blue represents "heater on" intervals.

its possible relation to climate. The study of PMSE is important for better understanding of, for example, the role of atmospheric waves in transporting energy and momentum to different parts of the atmosphere.

PMSE layers contain "fine structure" in height with spatial scales as small as 150 m. This structure can be resolved with the EISCAT VHF radar experiments using the unique, multi-frequency (max. 16) capabilities of the radar. In 1999 a special dual-frequency experiment was conducted by researchers from IRF to study the sharp discontinuities in the height profiles of PMSE. The technique is known as frequency domain interferometry (FDI) [27]. The IRF-led FDI measurements have served as a "spring board" for further multiple-frequency range imaging observations of PMSE made with the EISCAT facilities that are currently being conducted by other research teams.

In order to better understand PMSE micro-physics the first joint PMSE - ionosphere heating experiment was proposed and conducted in 1999 by a group of atmospheric physicists from IRF. The EISCAT Heating facility was used to increase electron temperature in the mesospheric region during "natural" PMSE events. PMSE were demonstrated to be affected by the heating pulses [22], see Figure 9. Further PMSE/heating experiments were conducted in 2001 and 2002 taking advantage of newly-upgraded EISCAT radar capabilities. The results obtained in PMSE-heating experiments [22, 28, 23] gave an impulse to other researchers to reexamine the role of multi-polar diffusion in generation of PMSE (Rapp and Lübken, Geophys. Res. Lett., 27, 3285-3288, 2000; Rapp and Lübken, J. Geophys. Res., 108, D8, doi:10.1029/2002JD002857, 2003). They also stimulated new EISCAT PMSE-heating experiments carried out by others groups (Havnes, J. Geophys. Res., in press; Havnes et al., Geophys. Res. Lett., 30, 2229, doi:10.1029/2003GL018429, 2003) as well as with another Heating facility in Alaska (Chilson, private communication).

Polar Mesosphere Winter Echoes (PMWE) have been found in the last three years primarily using the ESRAD MST radar (Kirkwood et al., 2002a). PMWE are very similar to PMSE but appear in the winter season at slightly lower altitudes. Although wintertime radar echoes at these heights were already reported 20 years ago (Ecklund and Balsley, 1981) it is only the newer observations which also reveal the likely role of aerosols in these layers (as for PMSE). The possible presence of significant aerosol layers in the winter mesosphere can be important for the radiative properties of the atmosphere, for possible effects on heterogeneous chemistry, and for correct interpretation of optical remote sensing measurements. It has become clear that the EISCAT VHF radar observes the same layers [29], offering the possibility for detailed studies comparing the different scale-sizes.

5.3 Active plasma turbulence physics

The section describes ground-based research which utilises the EISCAT-Heating facility to transmit a powerful HF (high frequency) electromagnetic wave (pump wave) into the ionosphere to induce perturbations so as to study fundamental aspects of plasma turbulence. Excitation of the turbulence by a transmitted electromagnetic wave enables control and repeatability of experiments, essential components of scientific endeavour. The EISCAT-Heating facility is the world's most powerful HF transmitter for research.

Such research seeks to understand self-organisation in turbulence due to interactions in a hierarchy of instabilities at widely different temporal and spatial scales. For example, a common feature of the hierarchy in such complex processes is that slower processes control the evolution of simultaneously-occurring faster processes. One may compare with our everyday life in which the process in our bodies of slowly becoming hungry, as time goes by, controls the faster process of taking a sandwich or an apple. The slow process of growing up and ageing, of course, exerts strong control over our everyday activities. In electromagnetically-driven upper hybrid turbulence in the ionosphere slow self-structuring into filamentary density depletions, so called striations, leads to localisation of fast oscillations in the turbulence inside the striations. An open research problem is to understand the interaction of the different striations with their trapped turbulence and the resulting grouping and organisation of the striations. This research is of general interest to plasma and nonlinear physics, in addition to space physics. For example, interaction of localised states might occur between lower hybrid solitary structures in the upper ionosphere and magnetosphere. In quantum mechanics one studies the interaction of bound and distributed states in atomic systems.

5.3.1 Langmuir turbulence

We performed one of the very first experiments in which pump-induced Langmuir turbulence was diagnosed with the unique tristatic radar mode of the UHF system [30]. An unexpected and most interesting result of the experiment, conducted during exceptionally quiet ionospheric conditions with low electron temperature, was that the excitation level varied significantly with respect to time and angle although the linear wave damping was small.

On the initiative of Brett Isham, a post-doc at the Swedish Institute of Space Physics, a chirp-generator was built and installed on the UHF and VHF radars. In the chirp technique individual radar pulses are frequency modulated, which enables simultaneous detection of the photo-electron enhanced plasma oscillations (characterised by background plasma properties such as temperature and density) and pump-excited plasma oscillations. The pump-excited plasma oscillations were found not to follow the linear dispersion characteristics of Langmuir waves in an essentially unperturbed background plasma, contrary to what had been suggested in the literature [31]. Further experiments provided unmistakable evidence of cavitating Langmuir turbulence at EISCAT [32].

5.3.2 Optical emissions

The first unambiguous detection of HF-induced optical emissions (enhanced airglow or luminescence) at auroral latitudes was obtained at EISCAT [34]. The optical emissions were detected with the multi-station Auroral Large Imaging System (ALIS) in the Kiruna area. The optical emissions were found to be due to upper hybrid turbulence which is different from the paradigm of Langmuir turbulence set by results from experiments at lower latitudes over the past decades. A surprising result was that the optical emissions occurred together with very large enhancements in the electron temperature of up to about 250 %, as measured with the EISCAT-UHF radar [35, 33]. Furthermore, the temperature enhancement extended astonishingly several hundred kilometres above the HF reflection height (as can be seen in Figure 10). These night-time findings can be used to test transport models for the ionospheric E- and F-region. Our initial experimental results on the optical emissions were quickly confirmed by others in experiments at EISCAT, HAARP in Alaska, and Sura in Russia.

The multi-station imaging with ALIS enabled for the first time tomographic estimates of the airglow volume shown in Figure 11 [33]. Measurement results for the oxygen green-to-red line intensity ratio imply that the optical emissions are due to a non-thermal electron velocity distribution [36]. Moreover, exper-

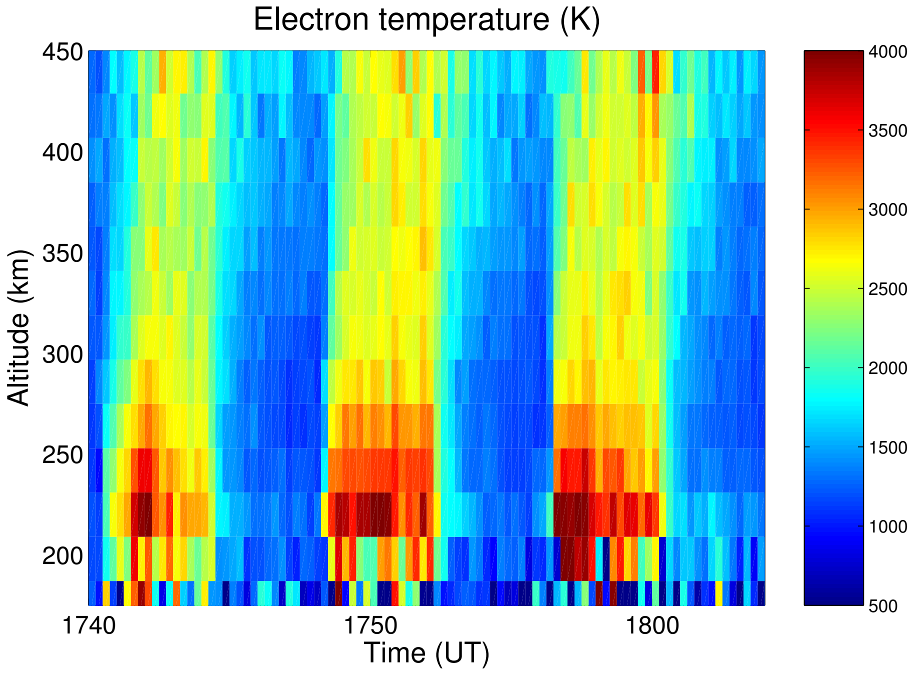

Figure 10: Very large EISCAT-Heating enhanced electron temperature during nighttime as measured by the EISCAT-UHF radar [33]. The reflection height of the pump wave is about 250 km. Notice the slow upward conduction of the electron heating following pump-on.

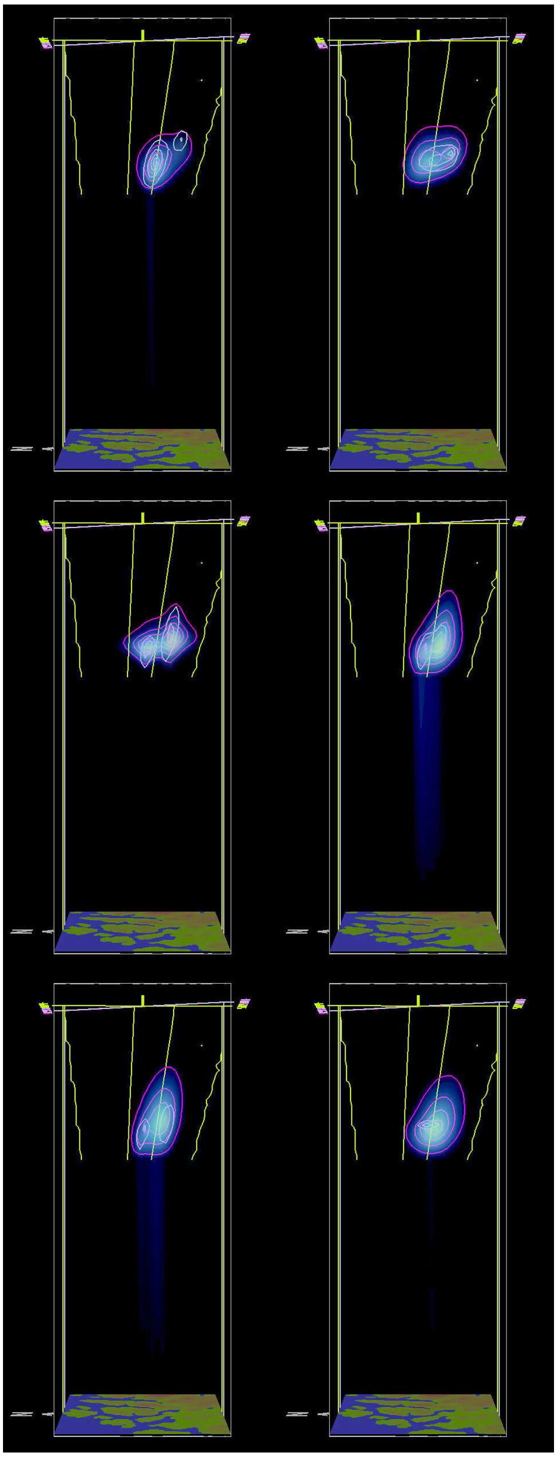

Figure 11: Volume rendering of the EISCAT-Heating-induced luminescence cloud at 6300 Å as seen from the west [33]. The bottom plane shows a map of the Tromsø/Kiruna region. The optical data was obtained by the multi-station ALIS in the Kiruna area.

iments performed in 2002 have given the first images of emissions at 4278 Å, i. e., of the ionisation of N_2 by HF pumping. The dependence of the 4278-Å emission intensity on the pump frequency near the ionospheric electron gyro harmonic gives input for the theoretical modelling of electron acceleration and contradicts interpretations in the literature on pump-induced ionisation. In addition to giving important information on the dissipation processes in plasma turbulence, the optical emissions also provide information of the background neutral atmosphere.

5.3.3 Theoretical results

The HF pump-driven upper hybrid turbulence in the ionosphere is strongly inhomogeneous since the oscillations may become self-trapped in filamentary density striations stretched along the ambient geomagnetic field. For the first time the nonlinearly-stabilised spectrum of small-scale density irregularities has been obtained [37]. It may be mentioned that several theoretical models for the initial instability evolution had already been published between 1975 and 1983. This paved the way for the self-consistent modelling of the structuring of the plasma density (due to thermal nonlinearity) and the ponderomotive interaction of upper hybrid waves trapped in the density depletions [38]. Such thermally self-localised upper hybrid states constitute a new mechanism in plasma physics for collective electromagnetic radiation, which may be of importance for interpreting the little-understood phenomena of stimulated electromagnetic emissions [39] as well as collective electromagnetic radiation from other plasmas (e. g. from magnetised planets, solar, and stellar surroundings).

The diffraction of an electromagnetic wave propagating in a plasma structured by small-scale filamentary density striations has been studied [40]. The diffraction leads to independent bunches of striations consistent with experimental results from Arecibo, EISCAT, and HAARP. Furthermore, we have obtained the first theoretical description of how the electron acceleration in trapped upper hybrid turbulence might occur, which can explain some of the results on enhanced optical emissions at high latitudes from e. g. EISCAT and HAARP [41]. The model takes into account the azimuthal mode structure of upper hybrid oscillations trapped in density depletions of striations and predicts an asymmetry in the acceleration efficiency around an harmonic of the electron gyro-frequency.

The long-standing problem of leakage of trapped upper hybrid oscillations into the electromagnetic Z mode has been solved analytically [42]. The modelling of this Z-mode leakage is absolutely necessary to describe the striations and shows that these are electromagnetically coupled over large distances. This result opens up the possibility of a global description of the self-organised plasma response to the electromagnetic pumping, including electromagnetic radiation and anomalous absorption phenomena that are so well developed in experiments at the high-latitude EISCAT facilities.

5.3.4 Plans for future experimental research

A purpose of this research is to study fundamental aspects of plasma turbulence driven by powerful electromagnetic waves in the ionosphere, particularly focusing on the self-organisation due to interactions in a hierarchy of instabilities at widely different temporal and spatial scales. This research is of general interest to plasma and nonlinear physics, in addition to space physics.

Research on the enhanced optical emissions at the auroral latitudes of EISCAT will be developed with focus on its use as a diagnostic of the complexity of the excited plasma turbulence. This includes tomographic inversion of prompt emissions to visualise spatial structure and organisation in the turbulence region. It is also most important to extract information of the ambient neutral atmosphere (thermosphere and mesosphere) since the optical emissions can be used to measure a variety of parameters which are not easily accessible by other means (without, e. g., chemical releases from sounding rockets). Also, it is of high priority to explore the potential of HF pump-induced ionisation as a diagnostic tool of different atmospheric constituents. To further this research it is beneficial to increase significantly the effective radiated power from the Heating facility.

It is expected that non-monochromatic pumping will play a crucial role in controlling different time scales in the excited turbulence. The use of pumping with various degrees of coherency in the transmitted pump wave is entirely new and has not been tested yet. Experiments with this technique rely heavily on recent progress in technology for signal synthesis and the possibility of suitable diagnostics, including the recent upgrade of the EISCAT radars to deliver raw data, to sample stimulated electromagnetic emissions at sufficiently high rate, and to be able to measure its polarisation and angular momentum.

In addition, the present research on the effects of powerful electromagnetic radiation on the ionosphere and atmosphere is significant for the solar power satellite that has been conceptualised to supply future energy needs. In the solar power satellite solar energy would be collected by solar panels in space without interference from diurnal variations and clouds. The solar energy would then be beamed to earth via, e.g., microwaves, to be fed into the power grid. In order to minimise losses it is essential to understand the interaction of the electromagnetic radiation with the ionosphere and atmosphere. It may be that the microwave will be modulated to minimise the energy loss. The exploration of non-monochromatic pumping to control different time scales in the excited turbulence is therefore of importance also to the solar power satellite in addition to fundamental plasma turbulence research.

It has long been recognised that the single most important experiment for advancing our understanding of the pumped plasma turbulence is to make in situ measurements in the pump–ionosphere interaction region. The proposed Swedish satellite Prisma would provide opportunities for measurements above EISCAT-Heating. In addition, efforts will be undertaken in the coming years to attempt sounding rocket launches from Esrange through the interaction region. It will be particularly important to make measurements of the strongly-inhomogeneous upper hybrid turbulence. According to theories, this turbulence

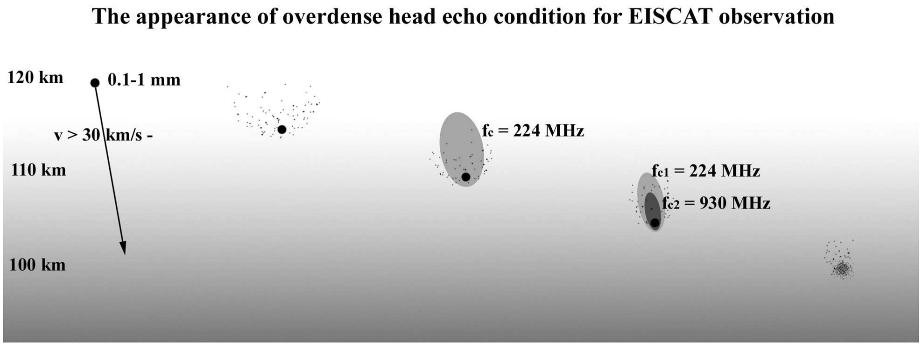

Figure 12: The meteor head echo scattering model based on EISCAT dual frequency observations is illustrated. The meteor head echo appears first at the VHF as the target reaches the overdense density and a few kilometres lower down at the UHF as the target plasma is compressed further to the corresponding overdense density.

is self-organised in filamentary density irregularities extended along the geomagnetic field, each containing quasi-trapped turbulence which act as antennas that couple the entire interaction region electromagnetically. These activities will consolidate the world-class role of EISCAT in ground-based space physics research well into this century and make EISCAT even more attractive for international research.

Plasma turbulence research with powerful HF waves needs increased maximum radiated power from the Heating facility to bring the turbulence excitation into new non-linear regimes, including ionisation of the upper atmosphere. It is also needed to increase the frequency range of the Heating facility, particularly toward lower frequencies, below the unexplored second electron gyro harmonic. A phased HF antenna array would provide entirely new possibilities to optimise the modulation of the transmitted beam, to control energy and momentum transfer to the ionosphere for exploration of the wave–ionosphere interaction. When upgrading the incoherent scatter radar systems it is most important to keep the capability of simultaneous measurement at two very different wavelengths, as with the present UHF and VHF radars. The different wavelengths probe different regimes of the turbulence, such as in cavitating Langmuir turbulence.

5.4 Meteoroid physics

The use of high power large aperture radars for meteor head echo observations was initiated by Swedish scientists using EISCAT in 1990. Much basic analysis on altitude distributions, velocities, particle sizes in order to understand the scattering process from the particles manifested as head echoes has been done since [43, 44, 45, 46, 47]. In studies of the extraterrestrial dust impact and orbital analysis of 10 meteoroids simultaneously observed with all the three EISCAT UHF receivers, 6 show hyperbolic orbits i.e. the particles are of interstellar origin [48]. Recently more studies focused on the scattering process have been finished [49].

Today, most of the incoherent scatter radar facilities in the world run meteor programs. A variety of space physics, aeronomical, astronomical and radio science issues have been and can be studied with the method. At EISCAT a head echo scattering model was introduced based on dual-frequency observations with the UHF and VHF systems [45] (see Figure 12). There have even been other competing models, but the EISCAT model was confirmed with a very detailed analysis on multi-frequency data from the ALTAIR radars (Close et al., J. Geophys. Res., 107(A10), 1295, doi:10.1029/2002JA009253, 2002) as well as with a theoretical work on full-wave solutions developed for scattering from meteor head plasma to determine the head plasma density and meteoroid mass (Close et al., Icarus, 2004). At Arecibo, orbital analysis on down-the-beam extrasolar micro-meteoroids and their interstellar origin was introduced (Meisel et al., ApJ., 567, 323, 2002).

After the stage of basic studies on meteoroid parameters and the interaction process, the method is mature for utilisation. Two different fields of application using EISCAT observations have been recognised, extraterrestrial dust studies and meteoroid flux impact on the near Earth environment.

5.4.1 Extraterrestrial dust studies

The major sources of the dust population in the inner solar system are comets and asteroids, but the relative contributions of these two sources have not been quantified. Observations near 1 AU provide clear evidence for the contribution of asteroids and short period comets to the dust cloud, which is concentrated in the ecliptic plane. On the other hand, it is difficult to estimate the cloud at high latitudes and the contribution from long period comets, which range to high latitudes, is not well established yet. The dust production from long-period comets is especially important for understanding the dust cloud composition inside the Earth orbit, where additional dust production is required to maintain the dust cloud and where comets are the most plausible source.

EISCAT has a good potential to become one of the most powerful instruments to study the off-ecliptic component of the interplanetary and interstellar dust distributions. The tristatic EISCAT UHF is the only facility at high latitudes with the capability to measure the 3-D velocity vector of meteors entering the radar beam. The present rates are about 1.5 tristatic observations per hour. This can be compared for example with Ulysses rates, which were about 1/day for small particles and 1/70 days for particles close to the size observable with radars. Here the 0.1 m^2 dust detection area size can be compared with the 1 km wide observation surface of the radar beam.

A measurement series of tristatic observations with a tristatic EISCAT radar at different locations along the Earth's orbit will provide a systematic study at high latitudes. The results in the form of orbits will give initial conditions for a phase space approach for investigating the global distribution of dust near the Earth's orbit, instead of just examining single trajectories. An important issue, not considered in previous studies, is the errors in the computed trajectories, for example, numerical errors, measurement errors and model errors. The simulation of the solar system dust cloud is of interest in the perspective of various planned missions to our closest neighbours in the space. Especially the dust environments of the inner planets Mercury and Venus are affected by the dust that can be observed at high latitudes.

Most of the tristatic meteoroids observed with EISCAT UHF come from the interstellar space outside the solar system. The analysis of these and their origin is of course of great interest. Based on the knowledge of today of the meteor head echo scattering process one can state that more and slower meteoroids will become observable by lowering the frequency. With a tristatic 224 MHz VHF radar the solar system meteoroid rates would increase with a factor of 10 as estimated from known mono-static relative EISCAT UHF/VHF rates.

5.4.2 Meteoroid/dust flux impact on the near Earth environment

This application focuses on the meteor process and its effects on the ambient space. EISCAT offers the only tristatic system that can look at the meteoroid passage through the radar beam with millisecond resolution and resolve from different aspect angles what is happening. This can also be used as input for a simulation of the impact as well as the retardation process of the meteoroids through the atmosphere down to the observation height. So far models have been used for this important step in the process for determining the orbital parameters. EISCAT can at the same time as observing meteors monitor effects on the background ionosphere: common increase of ionisation, sporadic E-layers, relative amounts of some metallic ion species etc.

There have been some essential differences between EISCAT observations and the results from all other comparable radars. The most dramatic is that EISCAT never observes meteor trails following the head echoes. At other facilities such as ALTAIR on the Marshall Islands and MU in Japan many effects like range spread trail echoes as well as field-aligned irregularities triggered by Farley-Buneman instability have been studied in connection to trail echoes. These radars are located at low latitudes and always measure close to perpendicular to the geomagnetic field lines when looking vertically. Probably the explanation for the riddle is that vertical observations at EISCAT have always been close to parallel to the geomagnetic field. The present EISCAT VHF radar cannot be pointed closer to perpendicular than about 30 degrees.

The meteor impact altitude zone is of great space technological interest as it is partly co-located with low Earth orbit satellite and Space Shuttle environments. By implementing a new multi-static VHF facility, the rates would increase for statistical studies. A phased array allowing adaptive beam forming would offer new dimensions for studying the meteoroid impact process within an expanded volume, perhaps even by observing the whole trail and ablation process. So far only an intersection of the process has been observed as the meteor passes the radar beam. In addition, a phased array could provide a chance for observations perpendicular to the geomagnetic field.

5.5 Applications

The EISCAT facilities are available primarily for basic research, but they have also been used for applied purposes (as well as for education, see section 5.6). A group of Finnish scientists signed a contract with the European Space Agency to investigate whether space debris can be detected and monitored using the EISCAT radars. A “piggy back” data acquisition system has been developed that can be fed with diverted regular EISCAT receiver signals. A special data analysis is performed that is needed for this task. Space debris is being noticed among the regular data from all incoherent scatter radars and depicts a more or less severe nuisance. If a systematic monitoring of debris and other objects in orbits around the Earth is desired, then EISCAT seems to operate some of the most capable facilities in the European sector.

Positioning and timing using satellites has turned into one of the most successful technologies that came out of the space age. The Global Positioning System (GPS) is the most popular one, and the European Space Agency together with the European Union are planning the catch up in the future with their own system named GALILEO. In Sweden a net of ground-based GPS stations has been deployed (SWEPOS) allowing for example a very high positioning accuracy even with simple portable GPS receivers. This is possible by comparing the signals from the portable and the stationary receivers. From the satellites the signals are transmitted at high frequencies, but when a very high accuracy is needed, corrections due to propagation through the ionosphere and atmosphere are still needed. Input for these corrections comes from models of ionospheric electron density profiles. A group of scientists at the Onsala Space Observatory is using EISCAT for verification of the model. In the future one can think of also correcting positioning signals based on real-time measurements of the electron density.

Nearly continuous measurements of the ionosphere with incoherent scatter radars are very desirable for many research goals, but particularly also for space weather services and applications like positioning and timing. The next generation EISCAT facilities need to be designed to be capable of operating a much larger fraction of the available time than is possible at present.

5.6 Education in space science and technology - potential for future EISCAT research

There has been a strong postgraduate educational program in Sweden connected to EISCAT since the beginning of its operations. Since 1982 close to 20 PhD theses have been defended, most of them dominantly EISCAT-related work. Most of these people have continued as scientists at IRF, two at EISCAT HQ and a few have moved to other companies: all of them have obtained highly-qualified positions. There is also now a Graduate School in Space Technology run by Luleå University of Technology that includes several PhD students working with EISCAT.

Undergraduate education in Sweden in space science and technology is presently undergoing a remarkable evolution. In times of decreasing interest among students, in the natural sciences in general and physics in particular, in Sweden and internationally, the number of students enrolled in space physics and technology education has increased from basically zero in the early 1990s to around 200 students at present. This offers an enormous potential to increase the outcome of Swedish EISCAT-related science. Umeå University offers a bachelors and a masters programme in Space Engineering and Luleå University of Technology offers a masters programme in Space Technology. This programmes are taught partly or entirely in Kiruna at the Space Campus close to the EISCAT facilities. Furthermore, there are space-related programmes or courses at Uppsala University, Royal Institute of Technology in Stockholm, Chalmers University of Technology in Gothenburg, and Växjö University. In addition, a popular senior high school education in Kiruna is "Rymdgymnasiet." All in all, this is a unique situation in Swedish natural science and technology education.

EISCAT is a very complicated instrument, which requires much training besides the need to understand plasma and space physics, techniques and signal processing. This has made EISCAT difficult to approach for those who have not been dedicated to it. Today EISCAT produces real-time plots of the basic plasma parameters, which makes it easier for scientists using other) instruments (space-born or ground-based) to compare their results with EISCAT. Still, the need to understand how an incoherent scatter radar works is essential for interpreting the data. Therefore, EISCAT summer schools have been organised in connection with most of the 11 biennial EISCAT International Workshops so far and one is already planned for the next workshop in Kiruna in 2005 at IRF. In addition, a course "Optics- and Radar-based Observations" was given for the first time in spring 2003 in the Luleå University of Technology Master of Sciences programme in Kiruna. This course was given in close interaction with the EISCAT HQ and a six hour experiment on the radar was performed as a laboratory exercise. EISCAT has also been presented in many basic courses in space physics and instrumentation as well as on an international summer course given by Umeå University in August 2003.

Recently the 1.4 GHz or, from astronomical point of view, the 21-cm receiver capability of the EISCAT Kiruna antenna has been utilised to investigate the distribution of neutral hydrogen in the Galaxy as a laboratory exercise in undergraduate courses. The interstellar neutral hydrogen is so abundant in the spiral arms so the 21-cm line has been observed in nearly all directions with radio telescopes. The interstellar medium is also relatively transparent to the 21-cm emission. These properties makes it suitable for mapping the arms of the Galaxy. The EISCAT receiver will record the radio intensity in a certain direction. The intensity will then be plotted as a function of frequency. The Doppler-shifted emission from the different galactic arms in the line of sight will then give information of the rotation velocity as a function of distance from the galactic centre.

The next step in radar competence is reached through a new general course in radar, "Radar Technology for Space Applications," which will be given in Kiruna for the first time in spring 2005 within the Technology Master of Sciences programme of the Umeå University. Planning of this course has already started in order to meet all the requirements of modern radar technology, generalised signal processing and scientific and commercial use of a set of various radars in the region. In case of further interest and need a PhD course has also been discussed.

6 Related Projects

EISCAT is today a part of various networks of tools for research in solar-terrestrial, atmospheric, and plasma physics. Much EISCAT-related research also involves other instruments on the ground and in space. In the following sections we present some projects that have been and are presently important for EISCAT users. We also take a look at tools and instruments that are likely to be available in the future.

6.1 Sounding rockets

Swedish Space Corporation's sounding rocket range, Esrange, is situated 20 km east of Kiruna. Sounding rockets and balloons flown at Esrange are used for studies relating to high latitude space and atmospheric physics and the chemistry of the upper and middle atmosphere. Esrange has served as the base for a large number of international rocket/balloon campaigns involving participants from, primarily, Europe and USA. The EISCAT radars are often used for ground-based support for the rocket experiments. They provide experimenters with complementary measurements of different geophysical parameters. One of the recent campaigns at Esrange was MaCWAVE (winter campaign). Mountain and Convective Waves Ascending Vertically (MaCWAVE) was a NASA campaign with European Co-Investigators. Its aim was an experimental study of gravity-wave forcing of the mesosphere and lower thermosphere (MLT). One measurement (among many others) was of electron density at MLT altitudes. This was measured in-situ with rocket-borne instruments and compared to measurements using a new EISCAT radar program for the lower ionosphere. Results using both techniques showed perfect agreement. This allows validated EISCAT data to be further used for more complex analysis.

The next Swedish rocket campaign, Mesospheric Aerosol - Genesis, Interaction and Composition (MAGIC), is planed for 2005. MAGIC aims to sample and to analyse meteoric particles and to relate their distribution to the atmospheric circulation. EISCAT again can serve as a complement instrument providing measurements of ionospheric parameters.

6.2 Swedish and other Space Missions

Over the past twenty years the Swedish national satellite programme has had some five missions for science and development of technology. Of these Viking, Freja, and Astrid II focused on space physics near the Earth, and especially Viking proved to be very valuable in connection with EISCAT observations for studying the aurora and substorms.

Presently the four Cluster satellites are the flagships of the European Space Agency (ESA) exploring the Earth's magnetosphere with excursions into the solar wind. The Cluster instrumentation has been developed and built with strong involvement by Swedish space research groups. The so-far highly successful mission is giving exciting results and providing data for analysis in many years to come. The Cluster satellites will probably stay alive until 2006.

ESA together with the Chinese space agency is launching Double Star consisting of two satellites in equatorial and polar orbits. The operational life time is 18 months. The scientific objectives of Double Star are to

- understand and locate the trigger mechanism of magnetospheric storms and substorms,
- study physics processes such as particle acceleration, diffusion, injection and upflowing ions during storms,
- study temporal variations of field aligned currents and the coupling between tail current and auroral current.

These scientific objectives can only be reached by also utilising ground-based observations, in particular from EISCAT.

In order to meet the requirements to have measurements covering as much spatial volume as possible in the magnetosphere-ionosphere system, every year about 200 hours of EISCAT observations are now dedicated to observations that are coordinated with the Master Science Plans of Cluster and in the future also of other missions.

6.2.1 TechnoSat/Prisma

The Swedish National Space Board plans to decide soon on the next (sixth) mission within the national satellite programme. This mission is expected to be developed and launched, with international cooperation, within the coming few years.

One of the top candidate missions consists of a micro- and a nano-satellite named for the time being TechnoSat and Prisma. A phase A study has been conducted. For the nano-satellite the phase B study has commenced. TechnoSat/Prisma will provide unique opportunities for coordinated measurements with the EISCAT facilities for research on natural and artificial plasma waves and turbulence. The orbits will remain below 1000 km altitude and cover high latitudes up to Northern Scandinavia, possibly even Svalbard. The satellites will have advanced, highly integrated and miniaturised radio wave instrumentation, gamma ray detectors, inter-satellite communication among other things. TechnoSat/Prisma is a technology explorer for future space instrumentation.

6.2.2 THEMIS

THEMIS is the acronym for "Time History of Events and Macro-scale Interactions during Substorms." The mission has been funded by NASA, and it is designed to answer fundamental outstanding questions regarding the magnetospheric substorm phenomenon. THEMIS will elucidate which magnetotail process is responsible for substorm onset at the region where substorm auroras map (at about 10 Earth radii, R_E). THEMIS's five identical probes measure particles and fields on orbits which optimise magnetotail-aligned conjunctions. Ground observatories determine the time of auroral breakup onset. Three inner probes at $\sim 10\ R_E$ monitor the onset of disruptions of the tail current, while two outer probes, at 20 and 30 R_E respectively, remotely monitor plasma acceleration. In addition to addressing its primary objective, THEMIS answers critical questions in radiation belt physics and solar wind - magnetosphere energy coupling. THEMIS is complementary to MMS (see below) and a science and is a technology pathfinder for future STP missions.

THEMIS will be launched in the spring/summer of 2006. The orbits will be optimised for magnetotail-aligned conjunctions over North America. However orbital and even magnetospheric dynamics will certainly also provide opportunities to study substorms in other sectors of the world including Europe. Through collaboration with members of the THEMIS science team, scientists in Sweden will be able to make use of the observations for their own research.

6.2.3 MMS

Resolving fundamental processes in space plasmas is the main theme of the Magnetospheric MultiScale (MMS) mission. The launch is planned for 2009, and MMS will be the most advanced so far in a series of multi-spacecraft missions for space physics research, after Cluster and THEMIS. Like Cluster, MMS consists of 4 satellites, but there will be many improvements: a broader range of orbital phases and spacecraft separations, a better time-resolution due to higher spin rates, and more advanced instrumentation and operations.

6.3 Ground-based Instruments

6.3.1 ALIS

The Auroral Large Imaging System (ALIS) is a unique facility intended for spectroscopic imaging of a variety of ionospheric optical phenomena, such as auroral emissions, radio-induced optical emissions and meteor trails. ALIS consists of several remote-controlled stations in northern Sweden, enabling observation of a user-selectable common volume above the mainland EISCAT sites. Overlapping fields-of-view enable three-dimensional reconstruction of the observed phenomena by triangulation and tomographic inversion techniques. A mobile station has been temporarily deployed at Skibotn for better coverage along the Tromsø magnetic field-line during several campaigns together with the EISCAT-Heating facility. Future plans for ALIS include improved time-resolution, better coverage along the Tromsø - Kiruna meridian, possible support for the proposed Esrange-Heating facility and a few more mobile stations.

6.3.2 ESRAD

The ESrange MST (Mesosphere-Stratosphere-Troposphere) RADar (ESRAD) is an atmospheric radar located at Esrange, just outside Kiruna in northern Sweden. It is owned and operated jointly by Swedish Space Corporation and IRF Kiruna (with substantial funding from the Swedish Research Council). It began operations in 1996. The purpose of the radar is to provide information on the structure and dynamic state of the atmosphere - winds, waves, turbulence and layering, from the troposphere up to the lower thermosphere (ca. 1–95 km altitude). ESRAD runs continuously and has contributed with data to many rocket/balloon campaigns, and to climatological and case studies. On several occasions it has detected PMWE (see section 5.2) simultaneously with the EISCAT radar.

6.3.3 MIRACLE

The Magnetometers - Ionospheric Radars- All-sky Cameras Large Experiment (MIRACLE) is a two-dimensional instrument network constructed for mesoscale studies of auroral electrodynamics. It is maintained and operated as an international collaboration under the leadership of the Geophysical Research Division of the Finnish Meteorological Institute. The network covers an area from subauroral to polar cap latitudes over a longitude range of about two hours of local time. The various instruments have different spatial resolutions, but basically the network is designed for studies in the spatial scales from a few tens of km upward. MIRACLE is planned to be operative until 2004.

6.3.4 NORSTAR

The ground-based optical and radio facility “The Northern Solar Terrestrial Array” (NORSTAR) is designed to remote sense auroral precipitation on a continental scale (i. e. North America). It consists of three CCD-based All-Sky Imagers (ASIs), four Meridian Scanning Photometers (MSPs), and 13 riometers. There are plans for seven more ASIs, mainly to complement observations with the THEMIS satellites. The ASIs and MSPs collect data at four auroral wavelengths (471, 558,630, 486 nm), at a cadence of 10-60 s/image. Three to four high-resolution ASIs will be deployed in close proximity on an extended campaign basis. This will allow for example resolution of the three-dimensional structure of auroras using tomographic inversion techniques.

6.3.5 PAI

The Portable Auroral Imager (PAI) is like NORSTAR a project at the Institute for Space Research provides of Calgary University, Canada, High temporal resolution optical measurements of auroral phenomena on a campaign basis. High sensitivity is achieved through the use of modern image intensifier technology in conjunction with a charge-coupled device. Similar systems are or have been in use by groups at Southhampton University and the Max-Plank-Institute of Extraterrestrial Physics.

6.3.6 Esrange Heating

The Swedish Space Corporation (SSC) has in its efforts to expand its activities raised the question of installing a Heating facility at its Launch Site Esrange in Kiruna close to one of the EISCAT receiver stations. This would provide a world-unique set of instruments for monitoring the Heating process simultaneously with rockets, an incoherent scatter radar and ionosondes, a MST and a meteor radar as well as optical instruments such as ALIS and all-sky cameras. In addition, simultaneous operation with the EISCAT-Heating facility would enable interesting ionospheric modification capabilities.

An informal meeting was held at IRF in Kiruna in December 2003, where an Esrange representative informed about the status of the project. IRF scientists from both Kiruna and Uppsala discussed technical questions such as location, frequency range, antennas as well as scientific topics such as how this facility could contribute to both atmospheric and plasma turbulence studies in relation to rocket and radar observations. A fully operational system could be running in a as short time as 1-2 years. As the scientific degree of interest for the project was high, SSC has decided to continue with a feasibility study.

6.4 Future Radars

6.4.1 LOIS

A LOFAR Outrigger in Scandinavia (LOIS) aims at enhancing the atmospheric and space physics capabilities of the giant digital radio telescope LOFAR (Low Frequency Array) by providing a software-configurable sensor and emitter network infrastructure distributed in southern Sweden with Växjö as hub. Primary target areas for LOIS are solar physics, ionospheric physics, and space weather as well as large-scale sensor, radio, antenna, telecoms, and IT research.

Both a scientific and technological synergy would result from LOIS and a phased-array facility at EISCAT. With LOIS the Sun's corona and the mid-latitude ionosphere can be actively probed, complementing the regions accessible to EISCAT. Both software and hardware technology and design of LOIS and of an EISCAT active phased-array could at least partially be shared, thus reducing costs and attracting more developers and educators.

6.4.2 AMISR

The Advanced Modular Incoherent Scatter Radar (AMISR) is a modular, mobile radar facility that will be used by scientists and students from around the world to conduct studies of the upper atmosphere and to observe space weather events (see Figure 13 for a conceptual drawing).

AMISR will be constructed in two stages over the next four years. The first phase will be constructed in Poker Flat, Alaska over the next 18 months. Following completion of the first phase, the remaining two phases will be built in Resolute Bay, Nunavut, Canada. Subsequent locations will be determined by a

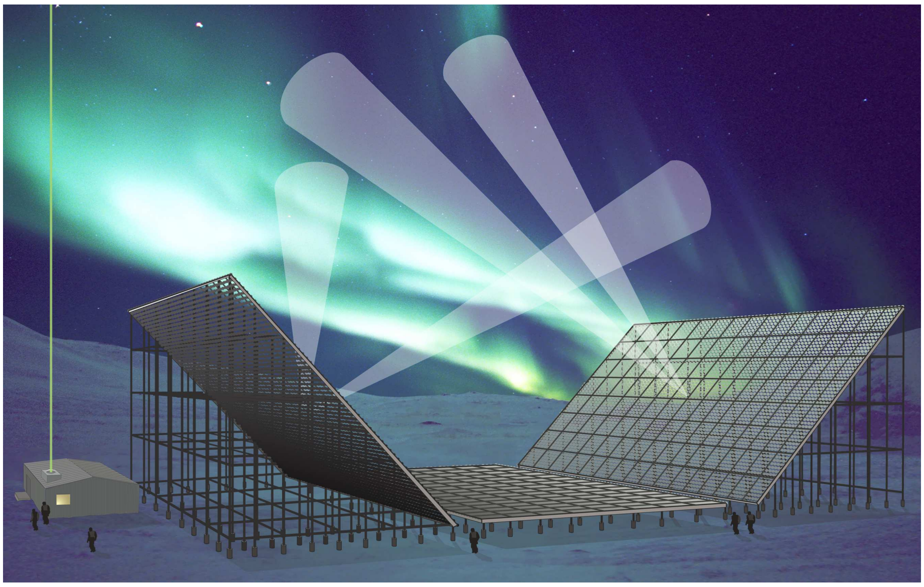

Figure 13: AMISR conceptual drawing with aurora Borealis in the background.

scientific advisory panel.

Our proposed new phased-array facility for EISCAT is based on the concept of AMISR and also of the Jicamarca radar near the magnetic equator in Peru, which already had an antenna array in the 60's. Technical parameters of a European phased array may differ, because of different regulations between Europe and North America concerning the use of radio frequencies.

In summary, researchers will also in the future have access to advanced instrumentation and techniques both on the ground and in space. In fact, it seems reasonable to expect that the importance of near Earth space physics and technology to humanity is likely to increase significantly. Many of the open questions in solar-terrestrial, atmospheric and plasma science can only be answered when a combination of new and existing, but upgraded, instrumentation is available. The EISCAT facilities are not only efficient stand-alone tools but are part of networks of facilities that are run and continuously extended by different research communities world-wide. In many respects the Northern European sector has been and is still equipped with unique instrumentation, and EISCAT is the outstanding example. The planned construction of similar facilities in other parts of the world does not mean that the relevant research in the future will be done equally well or perhaps better outside Europe. An increased coverage of the high-latitude ionosphere by new IS radars and other instruments is rather an opportunity to address important questions more globally than is possible at present.

7 Science Goals Summary

7.1 Geospace Physics

EISCAT related research in geospace physics beyond 2006 aims at

- ☞ using an incoherent scatter radar in the polar cap as a powerful monitor of the particle and energy input of the solar wind plasma into the magnetosphere-ionosphere-atmosphere system for space weather applications;
- ☞ studying the long-term effects of the direct exposure of the upper atmosphere to solar wind plasma, of ion upflow and atmospheric erosion;
- ☞ identifying possible effects on our atmosphere and magnetosphere of changes in the Earth's and Sun's dynamos;
- ☞ identifying the causes and effects in the physics of substorms and other geomagnetic disturbances;
- ☞ investigating quantitatively the momentum and energy balances between upper atmosphere and Near-Earth space;
- ☞ understanding the self-organisation into small scale structures in the auroral plasma.

7.2 Active geospace physics

Study the natural geospace environment by active stimulus–response experiments using powerful radio waves. This includes determination of parameter values of the ionosphere and upper atmosphere, stimulation of ionospheric currents, ionospheric layers, and aurora, as well as interaction with free energy sources such as precipitating electrons and feedback in the ionosphere–magnetosphere system. Such active experiments complement and expand on commonly used more passive observations of naturally induced phenomena in geospace using the incoherent scatter radars and other diagnostics alone.

7.3 Atmospheric Physics

In summary, in order to continue studies which have been fruitful in the past and to initiate new studies to serve the needs of atmospheric science EISCAT should

- continue regular CP observations with the EISCAT UHF (min. 1 day per month) for further studies of long-term trends in the lower thermosphere region;
- improve low altitude (mesosphere /stratosphere) capabilities by, e. g., implementing a phased-array VHF receiving site in Kiruna for further atmospheric dynamic studies;
- coordinate measurements with other high-latitude IS radars for study of global-scale waves;
- retain the Heating facility for further progress in PMSE-heating studies;
- retain the VHF radar for common studies of PMWE with ESRAD MST radar and measure the mesosphere often (e.g. 1–2 hours around noon, 3–7 days every week) and run a CP with the UHF at the same time.

As a general recommendation: EISCAT should improve the possibilities to run at short notice, when atmospheric conditions are particularly interesting.

7.4 Active Plasma Turbulence Physics

Active plasma turbulence physics studies fundamental aspects of plasma turbulence driven by powerful electromagnetic waves transmitted into the ionosphere, in particular focusing on self organisation due to interactions in a hierarchy of instabilities at widely different temporal and spatial scales. Outstanding research problems include the coupling of small-scale electrostatic and long-scale electromagnetic features of the complex turbulence as well as the dissipation and particle acceleration in the turbulence.

It is expected that future research will make increasing use of non-monochromatic pumping to control different time-scales in the turbulence and require the highest possible pump power. Diagnostics include incoherent scatter radars, detection of electromagnetic emissions with frequencies from ULF to above the optical, and, most importantly, in situ measurements using sounding rockets and satellites. It is essential that the ground-based measurements are made from multiple locations to enable interferometric and tomography-like analysis.

7.5 Meteoroid Physics

The characteristics of the interplanetary dust distribution are important for understanding solar system evolution and observing the solar system dust cloud in terms of its effects and risks on interplanetary missions. The characteristics of the dust impact on the near geomagnetic space environment are important for understanding different aspects of the meteoroid-atmosphere/ionosphere interactions and in terms of impact risks and low-Earth orbit effects on satellites.

High power large aperture radars such as EISCAT have proved to be useful in a wide range of applications concerning small particles entering the Earth's atmosphere from space. From being an ordinary incoherent scatter radar EISCAT could be improved greatly and even optimised for the meteoroid application by implementing a new multi-static VHF phased array system for the following reasons:

- The demand for a frequency spectrum for mobile phones at 930 MHz has decreased the original 30 MHz band to only 1.5 MHz. This can cause problems for estimating Doppler shifts for meteoroids at speeds of over 50 km/s. The VHF frequency assignment around 224 MHz is free from such threats.
- More and slower meteoroids will become observable as the frequency decreases. With a tristatic 224 MHz VHF radar the solar system meteoroid rates would increase with a factor of 10 as estimated from known monostatic relative EISCAT UHF/VHF rates in scattering volume comparable to the present VHF one. This would improve the method for general solar system studies.
- A measurement series of tristatic observations with the EISCAT radar at different locations along the Earth's orbit would provide a systematic study of the solar system dust cloud. This is interesting in the perspective of various planned missions to the closest planets. Especially the dust environments of the inner planets Mercury and Venus are affected by the dust fed by long-period comets, dust that can be observed from high latitudes on the Earth.
- A phased array allowing adaptive beam-forming would offer new dimensions for studying the meteoroid impact process within an expanded volume, even by observing the whole trail and ablation process.
- A phased array could provide observations perpendicular to the geomagnetic field, observations which are crucial for understanding the plasma physics in the meteor trails.
- The meteor impact altitude zone is of great interest for space technology as it is partly co-located with low-Earth orbit satellite and Space Shuttle environments. The rates would improve the statistics for input parameters for meteor influx models in space environment software.

8 Augmented Support for Swedish EISCAT Research

EISCAT is at the present one of the world's most versatile facility for ground-based space physics research. In view of the growing importance of space weather and the growing awareness of the crucial role of the near-earth ionosphere for magnetospheric dynamics and as the interface between the atmosphere and space plasma, EISCAT will be a key facility for space physics research also in this futute. EISCAT as an important big science project located partly in Sweden and the fascinating but complex auroral zone has an enormous potential for publicity and outreach for Swedish physics and geophysics research.

The Swedish EISCAT users have during the last few years achieved breakthroughs in various areas (e. g. meteor detection, PMSE modulations, stimulation of optical emissions) which are having a significant impact internationally. This diversity and influence is unique in the history of EISCAT-related research in Sweden. At the same time, the interest of Swedish undergraduate students in space physics and technology has never been as high as it is today. Recently there has also been an increase of the number of PhD students using EISCAT for their projects. This is happening thanks to financing by the graduate schools. Already these students increase the demand for EISCAT Special Program time for Sweden.

8.1 Increasing time for Swedish Special Programme

The present trend of science breakthroughs and the unprecedented large interest in space physics and environmental science among Swedish students constitutes an absolutely unique potential for EISCAT research. However this high potential can only materialise into fruitful fundamental science through a matched financial support. In view of the excellent prospects the time is right for augmented support for Swedish EISCAT research.

We propose that the amount of running time available for Swedish EISCAT users is doubled, from 210 hours to about 400 hours per year. Although this is a significant increase from the present Swedish share in EISCAT, we believe that such an increase would still be a most cost-efficient support in terms of scientific outcome in comparison to that of other big science projects in Swedish research.

In addition we propose that the suggested increase in the Swedish EISCAT contribution should be associated with augmented support for PhD students and post-docs. This would constitute a most timely boost of the scientific impact of Sweden in big science research world-wide as well as of the interest and fascination of the general public in the natural sciences.

8.2 Future hardware upgrades

In the international EISCAT community there has emerged an idea to construct a tristatic phased array radar at VHF, to consolidate the world-class role of EISCAT in ground-based space physics research well into this century and to make EISCAT an even more attractive facility for space physics research. In particular, the SAC of EISCAT has suggested that the implementation of such a radar system be pursued. We strongly support further considerations for such an interesting development of EISCAT.

9 Concluding remarks

Central questions that readers of this proposal are trying to answer is whether Sweden should even after 2006 remain a member of the EISCAT Association, and if so, what needs to be undertaken together with other members to make EISCAT a world-leading association even in the future.

For this document we have shown that EISCAT has been an invaluable tool for research in an increasing number of areas, and that the results are new, exciting and becoming of increasing practical relevance. The data that have already been gathered are needed for various long-term studies of the atmosphere, ionosphere, and solar wind, but the time span covered by EISCAT observations needs to be extended. A stable commitment of countries like Sweden to support the Association is both a prerequisite for measurements over long time spans and an incentive for the scientists in these countries to undertake such important studies.

Scientists in Sweden have led several projects that have resulted in breakthroughs and discoveries. Most of them are described in this proposal. This has only been possible because we have been able to conduct our own experiments and observations with the facilities. These discoveries were not made primarily at the beginning of EISCAT operations now more than two decades ago. Rather they have generally occurred when measurements from satellite missions and other instruments became available and when a technical development at the EISCAT facilities, usually implemented in order to achieve certain scientific goals, opened new possibilities. In addition, the development in signal processing and computational capabilities has pushed the radar resolution much closer to its fundamental limits. There are no signs that this trend of innovation in smaller steps but with great impact on science achievements is diminishing; rather the pace of scientific progress using EISCAT seems to have increased in recent years. We expect that even without major and costy upgrades and new facilities there are breakthroughs lying ahead in the years to come. We have therefore specified research goals that can be achieved if the present facilities are operated for several more years, often with help of other instruments and satellite missions that will be available in the near future.

For a number of ambitious and important science goals some limitations of the present facilities need to be removed, and it is now time for technical innovation to take a large stride. Priorities are to

- increase the spatial coverage, flexibility, and sensitivity on the receiving side of the facilities;
- operate nearly continuously over extended periods of time;
- greatly increase the spatial resolution using interferometer techniques;
- increase spatial and temporal flexibility in transmitting the signals;
- increase the effectively transmitted power.

Not everything that has been mentioned in the document can probably be realized, but there is also likely to be much scientific and technical potential in the multi-static phased-array facility proposed here that we have been unable to fully foresee.

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Appendix I, Program of Swedish Workshop about future EISCAT-related research held 24–25 April 2003

10:00 Welcome, Short Introduction to EISCAT (Asta Pellinen-Wannberg)

Session 1, Introduction (Chairperson Lars Blomberg)

10:20-10:55 Swedish and International Space Research, Bengt Hultqvist

10:55-11:30, Whither EISCAT? Tony van Eyken, Director, EISCAT Scientific Association

11:30-12:05 Future radar technique and signal processing at EISCAT, Gudmund Wannberg, Deputy Director, EISCAT Scientific Association

12:05-13:05 Lunch

Session 2, Science cases (Chairperson Tord Oscarsson)

13:05-13:40 Solar system physics with EISCAT, Asta Pellinen-Wannberg, IRF, Solar System Physics

13:40-14:15 Radars for atmospheric research, EISCAT's past contribution and future potential, Sheila Kirkwood, IRF, Atmospheric Research Programme

14:15-14:50 Active experiments for environmental research in geospace, Thomas Leyser, IRF, Physics in Space

14:50-15:25 Remote sensing of geospace, Stephan Buchert, IRF, Space Plasma Physics

15:25-15:45 Coffee break

15:45-16:20 EISCAT-ALIS combination for ionosphere-magnetosphere research: results and perspectives. Tima Sergienko, IRF, Sun-Earth Interaction Program

16:20-16:40 Presentations of young scientists and their research (Csilla Szasz, Johan Kero, Carl-Fredrik Enell, Abhay Kumar Singh, ca 5 min. each)

16:40-18:00 Free discussion of the science case for EISCAT after 2006, Chairperson Stephan Buchert

19:00 Dinner at the restaurant Lingon, Svartbäcksgatan 30

Friday, 25 April 2003

Session 3, Science, Technology and Education (Chairperson Evgenia Belova)

9:15- 9:50 EISCAT as a tool for scientific and technological education in Sweden, Ingrid Sandahl, Director, Kiruna Space and Environment Campus

9:50-10:25 Technical and scientific collaboration between EISCAT and ESRANGE, Ola Widell, Science Coordinator, Esrange, Swedish Space Cooporation

10:25-10:50 Coffee break

10:50-11:25 On the exploration of polarisation diversity and MIMO in space communications, Sven Nordebo, School of Mathematics and Systems Engineering, Växjö University

11:25-12:00 Ionospheric corrections in radio navigation and space geodesy, Jan Johansson, Onsala Space Observatory

12:00-13:00 Lunch

13:00-15:00 Free discussions of EISCAT related technology, education, and science organisation as well as contributed presentations, Chairperson Asta Pellinen-Wannberg

Appendix II, Swedish EISCAT related publications 1999–present

Brändström, B. U. E., T. B. Leyser, Å. Steen, M. T. Rietveld, B. Gustavsson, T. Aso and M. Ejiri, Unambigous evidence of HF pump-enhanced airglow at auroral latitudes, Geophys. Res. Lett. , 26, 3561-3564, 1999.

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