INCOHERENT SCATTER RADAR OBSERVATIONS OF THE CUSP IONOSPHERE

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ABSTRACT/RESUME

Incoherent scatter radars are a powerful ground-based tool to probe the Earth's ionosphere. A great amount of observations from the high latitude ionosphere has been collected with the EISCAT radars on a regular basis by so-called Common Programmes as well as by operations for special purposes. We present results from observations of the upper F region and topside ionosphere, locations which will be crossed by the SWARM satellites.

The EISCAT measurements of ionospheric plasma parameters like electron density and temperature, and ion velocity and temperature will be useful to calibrate the CEFI instruments on the SWARM satellites when operation is scheduled for passes over the radar facilities. Another important way of using the EISCAT facilities in connection with SWARM is to measure accurately the conductivities. Together with measurements of the electric field by EISCAT and/or CEFI one can so obtain an independent estimate of the contribution of ionospheric currents to the magnetic field at the satellites. Also for the study of ionospheric plasma physics the use of EISCAT and SWARM data promises to be fruitful.

1.THE EUROPEAN INCOHERENT SCATTER FACILITIES

When radio waves are transmitted through the ionosphere, then two cases can be distinguished. If the wave frequency is below the highest plasma frequency of the ionosphere then a well-known reflection occurs. In the fivties of the 20th century it was recognised that a weak quasi-incoherently scattered signal is detectable when the frequency, normally VHF or UHF, is above the highest plasma frequency. "Incoherent Scatter" refers to the physical process that scatters electro-magnetic waves above the plasma frequency.

While incoherent scattering has proved to be extremely useful for probing the ionosphere, a high transmitter power (~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. The EISCAT (European Incoherent SCATter) facilities comprise three incoherent scatter radar systems and one powerful radio pump facility in northern Europe. Fig. 1 shows the locations of the radars.

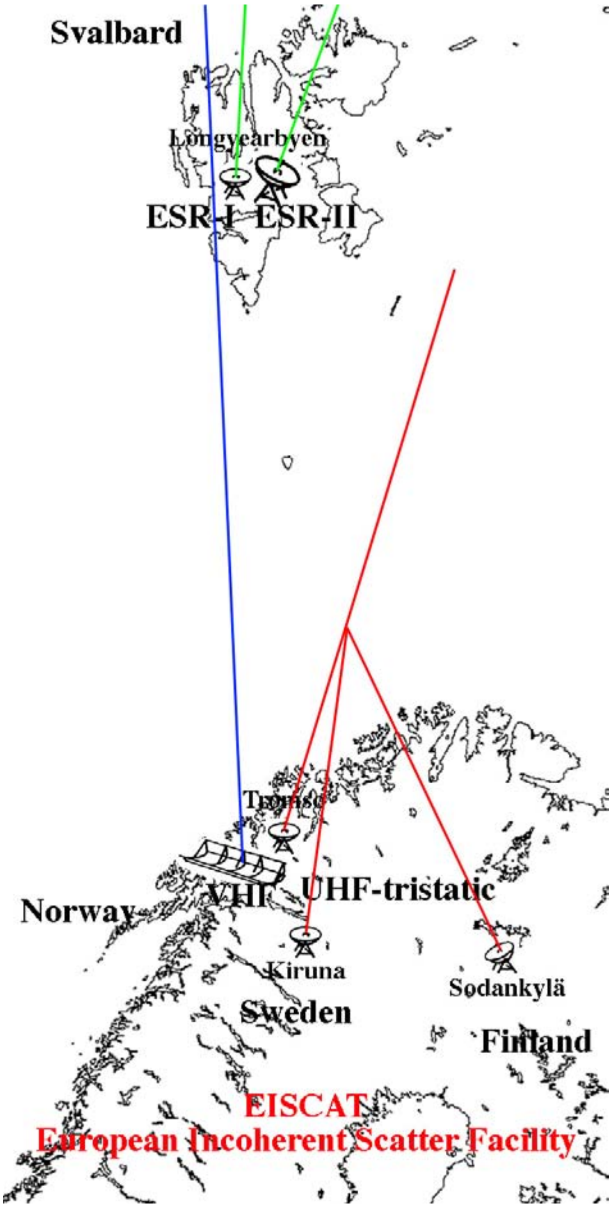

Figure 1. Locations of the EISCAT UHF and VHF radars on the mainland and Svalbard radar (ESR)

The radars measure routinely parameters in the E and F regions of the ionosphere, namely electron density *(Ne)*, ion and electron temperatures *(Ti* and *Te),* and the ion velocity (*Vi)* along the line-of-sight or the scattering vector. The full velocity vector is derived by combining the velocities from the tri-static UHF radar Alternatively at least three different antenna pointing are made to derive the velocity vector, but then one has to assume that the plasma velocity is constant over some region in space and time interval. From these directly estimated parameters also the electrical conductivities and currents, and the neutral wind can be estimated. This requires knowledge of the densities of the atoms and molecules in the thermosphere, and the neutral temperature. Their variations depend on the solar zenith angle, solar and geomagnetic activity etc. A model based on a large amount of data from mass spectrometer and incoherent scatter radar data, with the acronym MSIS, is being maintained and conveniently used to provide this information. Fig. 3 shows schematically how the with radar directly measured plasma parameters are combined with models in order to estimate a wide range of further parameters relevant for the dynamics of the thermosphere and the coupling between the ionosphere and magnetosphere.

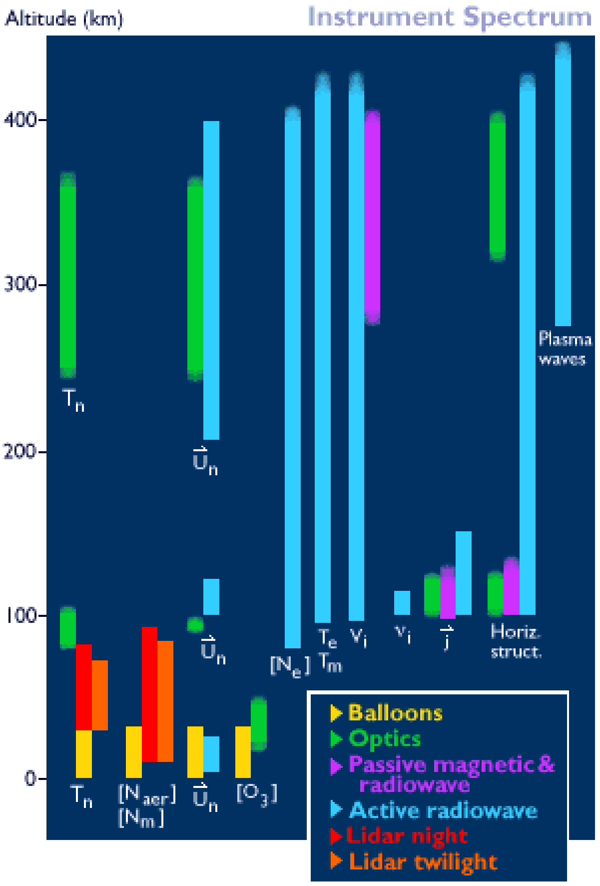

Figure 2. Atmospheric and ionospheric parameters measured by ground-based techniques (chart from SRI, http://isr.sri.com)

The EISCAT radars have been operating roughly 2000 hours, or about 80 days, per year, each the ESR and the mainland UHF/VHF facility. About half of this time is devoted to so-called Common Programmes, aimed at investigating the variations of ionospheric and thermospheric parameters and their possible trends over long times like a solar cycle. These data are made accessible to everyone and are archived in MADRIGAL which is a data base of ground-based measurements and models of the Earth's upper atmosphere and ionosphere including MSIS. One of the access points is http://www.eiscat.se/madrigal.

EISCAT is funded by Associates which are China, Finland, Japan, Norway, Sweden and the UK. A new agreement effective from the year 2007 onwards has been signed. It guarantees a certain level of funding for at least five years which is the period of notice if an Associate wishes to change its contribution or withdraw. Thus the EISCAT facilities will very likely be operational when the SWARM mission starts and also well into its life time.

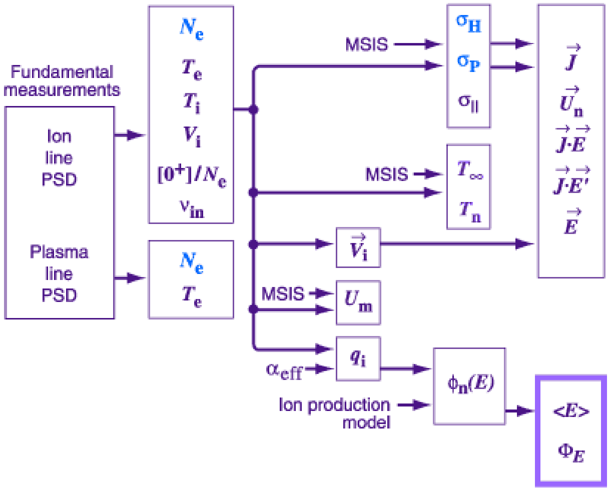

Figure 3. Flow chart of incoherent scatter data analysis and parameter estimation (chart by Jeff Thayer).

2.EISCAT AND SWARM

2.1 Calibration

The Canadian Electric Field Instruments (CEFI) on SWARM will determine the ion drift velocity through precision measurements with a novel electrostatic analyzer capable of forming 2-D images of ion distribution functions. The CEFI ion measurements will be supported by two Langmuir Probe sensors and electronics. The LP will measure spacecraft potential along with electron temperature and plasma density. Thus the CEFI measures essentially the same parameters as the incoherent scatter radar, and there will be unique opportunities to compare measurements from ground-based radar measurements with advanced in-situ observations from the CEFI for mutual calibration and also for addressing important scientific questions.

The techniques are very different from each other. Radar measurements of *Ne, Te, Ti* and V*i* are relatively noisy at the altitude of the SWARM orbits. But they are believed to be free from any biases, while satellite instruments could be affected by spacecraft charging, wakes from booms, shadows etc. Therefore it will be possible to calibrate CEFI data by comparing them with radar data from the same spatial volume at the same time. However, some limitations will exist.

The time resolution of the in-situ measurements and the orbital configuration allow to resolve horizontal structure in the thermosphere and ionosphere with a considerably higher resolution than it is possible from the ground. Also, the heavy EISCAT antennas will not be able to track the SWARM satellites in real time. The antennas can be directed to a single volume of a few kilometers size that is crossed by one of the satellites. Thus one EISCAT radar can essentially provide one data point per SWARM overflight representing an average in time and space compared to the highly resolving in-situ data. We expect that after a few tens of overflights the accuracy will be sufficient for a useful calibration.

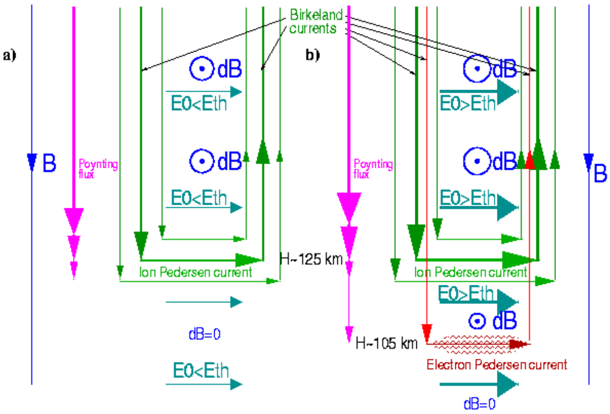

Figure 4. Schematic drawing of field-aligned current closure at high latitudes. a) Normal closure by ion Pedersen current when no electrojet instabilities are excited. b) With additional electron Pedersen current flowing across the auroral electrojet.

2.2. Plasma anisotropy

EISCAT observations as in [1] have shown that under relatively common circumstances, when there are high electric fields perpendicular to the geomagnetic field ***B***, the ion distribution function becomes non-Maxwellian and anisotropic with respect to the direction of ***B*** due to so-called pickup of ions from the neutral gas. At high altitudes above the F region peak the occurrence of anisotropy seems to be related to upflow of ions along ***B***, possibly caused by anisotropic pressure, the magnetic mirror force, and/or plasma waves generated by the free energy in the distribution function [2]. CEFI will measure the full ion distribution function and thus provide new opportunities to investigate the phenomena of non-Maxwellian plasma and ion upflow at high latitudes, particularly when coordinated campaigns with the EISCAT facilities are performed.

2.3.Estimating auroral currents using incoherent scatter radar data

A major goal of the SWARM mission is to separate internal and external contributions to the magnetic field ***B***. At high latitudes, in the auroral zone and the dayside cusp, relatively strong spatial and temporal variations of ***B*** arise from current systems consisting of field-aligned or Birkeland currents that extend far into the magnetosphere and the near Earth space and close via Pedersen currents in the lower ionosphere below the SWARM orbits. These current systems also involve the transfer of electromagnetic energy from space into the ionosphere and upper atmosphere where the Poynting flux converges and the energy is dissipated into heat. In addition dissipation-less Hall currents flow in the E region, and their magnetic effect can still be significant at the altitude of the SWARM satellites.

When the electric field which is dominantly perpendicular to ***B*** and the Pedersen and Hall conductivities of the lower ionosphere are known, then the currents and their magnetic effect can be calculated in principle. For full accuracy, however, the electric field and conductivities over an area of a few hundred kilometers below the satellites are needed. Methods for assimilating data from ground-based magnetometers, the coherent SuperDARN radars, and other sources are mainly the Kamide-Richmond-Matsushita (KRM) method and AMIE (Assimilative Mapping of Ionospheric Electrodynamic). These methods are in principle capable of providing independent estimates of the external component of ***B***, but the present versions do not continue the magnetic field calculation upward from the E region, and the spatial and temporal resolutions are limited.

Auroral field-aligned currents flow mainly in sheets roughly elongated along east-west and crossed by the satellites. A 2-dimensional system as shown schematically in Fig. 4 is in practice a good approximation. Ref. [4] has shown that the electric field and magnetic variation are orthogonal to each other and highly correlated, in agreement with the scenario of stationary, vertical up- and down current sheets closing in the E region. With these simplifying assumptions the relation $\delta B = E/\mu_0\Sigma_P$ holds, where δB is the magnetic variation normal to ***B*** and the satellite track (which is assumed to be normal to the current sheet), E the electric field orthogonal to δB, and Σ_P the height-integrated Pedersen conductivity. Thus an independent estimate of the external variation δB from auroral currents can be obtained when E and Σ_P are known. The radar can measure Σ_P which depends on Ne and the densities of the neutral species, but has also a contribution caused by the excitation of irregularities in the auroral electrojet as pointed out in [5] and shown in the right panel of Fig. 4. Both CEFI and EISCAT can provide E. At overflights of SWARM over EISCAT one can thus hope to obtain relatively accurate, independent estimates of the auroral δB using measured E and Σ_P. Such opportunities would be useful to verify methods providing the external δB everywhere by extrapolating E from CEFI, possibly using the KRM or AMIE technique, but relying on models of Σ_P. By the time when SWARM is in orbit we also hope to have improved models of the ionospheric conductivities at high latitudes using the large amount of accumulated incoherent scatter data described above. In summary, incoherent scatter data are the most accurate source for the ionospheric conductivities and thus will complement the SWARM measurements particularly in the auroral zone.

2.4 Small current structures and plasma instabilities

Very short-lived enhancements of the received power seen by the EISCAT radars have originally been a surprise and are still studied by several research groups. The received spectra become coherent-like and are probably due to plasma waves. Ref. [5] used the two antennas of the EISCAT Svalbard Radar in interferometer mode and found that the enhancements extend sometimes as little as a few hundred meters across $\boldsymbol{B}$, less than the beam size of the antennas. With the rapidly sampling magnetometer on CHAMP [5] have detected very intense field-aligned currents of about one km or less scale-size. When these currents are seen then usually also a strong increase of the neutral density and upwelling of the thermosphere is happening. It has been suggested that the plasma waves causing the power enhancements in radar data are excited by instabilities from currents with an intensity of at least several hundred μAm^{-2}. Therefore it is quite possible that both, the intense small-scale currents seen by CHAMP and the plasma waves detected by the radar are related phenomena. Fig. 5 shows an example of enhanced ion-acoustic lines in ESR data. CHAMP data only 10 minutes earlier at close distance to the ESR reveal intense narrow FACs as well as thermospheric upwelling (H. Lühr, personal communication). In the two inlets of Fig. 5 the spectral power is colour-coded over frequency on the abscissa and altitude from about 300 to 1200 km on the ordinate for two events each lasting 6 s or less. The enhancements occur above the F region density peak once on the down-shifted and once on the up-shifted side. The panels in the background show electron density, temperature, and ion velocity over UT (abscissa) and altitude (ordinate). When the plasma waves are seen in form of power enhancements, the electron density and temperature are high in the upper F region due to particle precipitation, and ions move upward along $\boldsymbol{B}$. Thus the occurrence of small scale structures is associated with ionisation and heating of the plasma and neutral gas, and this might be a cause of ion upflow and upwelling of the neutral atmosphere.

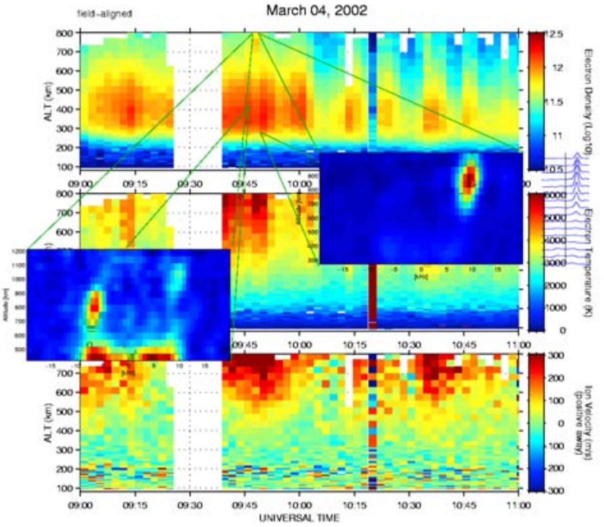

Figure 5. ESR observations of ion line enhancements (shown in the two foreground panels) occurring in a period of high electron density and temperature and ion upflow (shown in the background panels).

However, the processes are far from being well understood, and there are no clear in-situ observations of such high altitude plasma waves seen with the EISCAT radars. Prospects are good that the SWARM satellites will provide new in-situ observations of these small structures with large effects.

3.CONCLUSIONS

We have briefly presented the ground-based EISCAT radars and their expected potential when being used for supporting the SWARM mission. The CEFI and its Langmuir probe on SWARM measure plasma parameters that are also derived from the signal received by EISCAT. The incoherent scatter technique has very successfully been used for several decades and radar data are expected to serve as calibrating standard for the new technique used in the CEFI. In addition to the calibration aspect, three topics have been pointed out where the combination of SWARM and EISCAT data is expected to enable scientific advances. The topics are 1) non-thermal ion distributions, ion anisotropy and upflow in ionosphere; 2) auroral current systems and ionosphere-magnetosphere coupling; and 3) small scale currents and plasma waves. Investigations of these phenomena will benefit from coordinating special EISCAT experiments with passes of the SWARM satellites near the radars.

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