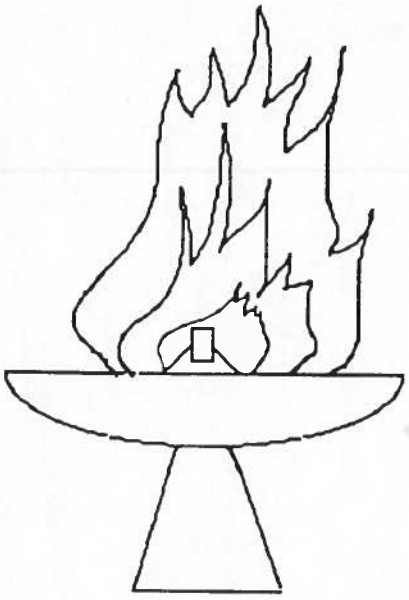
# An HF Heating Facility for EISCAT

## The Scientific Case



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# 1. INTRODUCTION

The investigation of the modifying effects of high power radio waves in the ionosphere has been motivated by a number of scientific and technological objectives. These include the production of an artificial communication channel in the otherwise highly unpredictable natural ionosphere and the simulation of the effects of extremely high power transatmospheric microwave beams such as that envisaged for the proposed Solar Power Satellite. However, by far the most attractive and scientifically exciting motivations are the utilization of the ionosphere as a natural plasma laboratory to study a variety of important nonlinear plasma phenomena and active aeronomical experimentation for studying the response of the ionosphere to a well defined heat source. By this means the generation, stabilization, morphology, dynamics and spectral characteristics of plasma waves and irregularities on a wide variety of spatial and temporal scales may be investigated.

What makes the ionosphere particularly attractive in this respect is its homogeneity and relative permanence, unlike laboratory plasmas which tend both to have small dimensions in relation to wavelength scales of interest and to be short lived. Currently, the most powerful and versatile ground based high power facility [heater] is that built and operated by the Max-Planck-Institute for Aeronomy, Lindau [MPI] at Tromsø in Norway. This heating facility, which can transmit an effective radiated power [ERP] of 300 MW in the frequency range 3.8-8MHz into the ionosphere, is colocated with the EISCAT UHF and VHF incoherent scatter radars at Tromsø [see figure 1], and the combination of MPI heater and the EISCAT diagnostics provides a uniquely powerful tool to probe new nonlinear plasma phenomena and to undertake active aeronomical experiments in the ionosphere.

Since the MPI heater became operational in 1980 a number of new discoveries have been made. These include stimulated electromagnetic emissions with highly structured spectra, thermal cavitation, induced low frequency emissions from the auroral electrojet, field aligned irregularity hysteresis, ion line intensity overshoot and a variety of parametric effects which give rise to drastic modifications to incoherent backscatter spectra. The EISCAT UHF radar, and to a more limited extent the VHF radar, have played a major role in diagnosing many of these phenomena. Heating observations provide an immensely rich source of information concerning not only the basic physics of complicated nonlinear phenomena associated with poorly understood processes like plasma turbulence but also the structure and dynamical properties of the natural ionosphere. Much has been learned from heating experiments at Tromsø over the past nine years but much still remains to be done. For this reason, although the MPI heating project is reaching the end of its planned duration [1993], MPI are currently upgrading the heater to enable it to transmit up to 1200 MW ERP. This should greatly increase the variety of instabilities that may be excited, as well as extending the plasma physics further into the nonlinear regime.

MPI have now offered to hand over the heater to the EISCAT Scientific Association in 1993 to allow modification studies to continue to the end of the century. Scientists from a number of the EISCAT countries have been heavily involved in the MPI heating project since 1980 and have contributed enormously to its internationally recognized success. In addition, scientists from member countries have gained a great deal of experience in cooperating in the running of collaborative heating campaigns. The restructured EISCAT/Heating facility and in particular the increased accessibility to heater time, which is a major advantage of the proposed new arrangement, will encourage an even wider cross-section of the EISCAT

community to participate in heating research in the future.

The purpose of this document is to set out details of what scientific progress has been made so far in the Tromsø heating project and to discuss how it might be used in the future as a new [third] EISCAT facility.

## 2. THE HEATING FACILITY AND ITS FUTURE

It is certain that the physical problems studied in ionospheric modification experiments will not be exhausted in the near future. However, the present heating group at MPI, after 15 years dedicated exclusively to the programme, wants to be relieved of the duty to keep the facility going and to be present at every experiment that is done with the facility. Consequently, MPI is attempting to continue the Heating project by handing it over to an organization which will make the facility available to everyone interested in such experiments, including scientists from MPI. The continued interest of MPI in Heating work is evidenced by the fact that MPI is still strongly investing in the facility. There will soon be a new antenna array that will allow to produce an ERP of 1200 MW [Spring 1990].

### 2.1 Schedule for Takeover

MPI intends to run the Heating facility until the end of 1992. EISCAT could partly take over before 31.12.92. There would then be an intermediate period of joint responsibility. However, practical difficulties are anticipated with such an arrangement and it would be preferable for EISCAT to take over on 1 January 1993. Furthermore, a period of one to two years before that date should be used to train new technical staff.

### 2.2 Technical data

The HF high power facility comprises a bank of 12 transmitters which feed three separate antenna fields, depending on the frequency and effective radiated power [ERP] required. The transmitters are capable of being operated continuously or in a modulated mode. The facility is designed mainly for CW operation so that if the transmitter output is modulated into pulses the peak power cannot exceed the CW power. The minimum pulse length available is 20 μs but there is no limit on the duty cycle. Either linear or circular polarization may be transmitted.

After the completion of the present construction work[Spring 1990] the technical data will be as follows:

CW power 1.2 MW
Frequency range 3.8 - 8.0 MHz
Antenna Array 2: 36 crossed dipoles, 3.8 - 5.5 MHz, ERP = 300 MW
Antenna Array 3: 36 crossed dipoles, 5.4 - 8.0 MHz, ERP = 300 MW
Antenna Array 1: 144 crossed dipoles, 5.4 - 8.0 MHz, ERP = 1200 MW

Array 1 constitutes the new Superheater referred to later.

### 2.3 Costs and Resources

It is not the purpose of this document to go into detail concerning matters of funding and resources. The current best estimates of these requirements are contained in the paper

presented by the Director to the EISCAT Council [October 24, 1988]. The overall financial requirements involve an initial capital investment of between 1.5 to 2 MNoK, with yearly running costs estimated at around 1.7 MNoK. The running costs include the salaries of the new personnel who will have responsibility for maintaining the heating facility and liaising with visiting scientists. The personnel comprises one scientist with three other staff involved in technical and secretarial support. It is essential that an EISCAT scientist with experience of heating research be dedicated full-time to running the heating project if the best possible use is to be made of the new facility.

# 3. SCIENTIFIC GOALS AND ACHIEVEMENTS

## 3.1 Scientific goals

Heating work so far carried out at Tromsø has addressed two broad areas of scientific study. Firstly, a variety of nonlinear wave-wave interaction processes which involve questions of plasma physical interest have been investigated. One such area of work has concerned parametric instabilities driven by the high power electromagnetic wave [pump] through so called ponderomotive coupling effects. These generate plasma waves on short time scales [~ ms] . Both the EISCAT UHF and VHF radars have been employed to directly detect the intense short-scale [32 cm] plasma wave fluctuations which result [see figure 2]. In addition, the entirely new technique of stimulated electromagnetic [HF] emission, which was first discovered at Tromsø, has been used extensively to investigate the highly structured pump induced wave spectra. A second aspect of plasma physical interest which has been extensively investigated at Tromsø has been the generation of field aligned irregularities by thermal parametric instabilities where coupling occurs through spatially modulated heating. Field aligned plasma irregularities are also a ubiquitous phenomenon in the natural ionosphere, especially at high latitudes, and have consequently proved of immense interest from the aeronomical point of view. This aspect of the study of plasma irregularities will be dealt with subsequently.

The second area of scientific interest has been what can broadly be called active aeronomical experimentation. Here the response of the ionosphere to the intense heating effect of the powerful radio wave produced by the high power facility has been studied, both because of the novelty of the effects themselves and because of the light they can shed on naturally occurring plasma processes such as ionospheric chemistry, particle collisions, diffusion and heat conduction. Of particular interest has been the generation, in the F region, of field aligned plasma irregularities on a wide range of spatial scales, ranging from a few metres across the geomagnetic field to the width of the heater beam itself [40 km]. A further area of fruitful active aeronomic experimentation has been the modulation of the auroral electrojet. This effect is achieved through the modification of the temperature dependent conductivity in the lower ionosphere and allows ULF and VLF waves to be generated by modulating the heater which in turn modulates the electrojet current. Tromsø is of course ideally located for this type of experiment. In these active aeronomy experiments, a wide variety of experimental techniques have been employed to diagnose the heating effects, in addition to the EISCAT radars themselves. These diagnostics include coherent radars, low-power HF radio systems, ionosondes, scintillation receivers [both for radio stars and satellite beacons], magnetometers, the partial reflection experiment [PRE] and also rocket borne probes.

Some of the major highlights of heating experiments carried out so far at Tromsø are outlined below.

## 3.2 Plasma Physics Experiments

### 3.2.1 Parametric instabilities

The general theory of parametric instabilities in plasmas was first studied in the 60s [Dubois and Goldman, 1965; Silin, 1965] and was later applied to the ionosphere [Perkins et al, 1974; Fejer, 1979]. Since the very first experimental observations in 1970 of the parametric decay of the heater wave into electron and ion plasma waves, at Arecibo, there has been a rapid development within this area of space plasma physics. In particular, with the advent of the MPI Heating Facility in Tromsø around 1980, new and unique opportunities for studies of nonlinear wave interactions were opened up. Not only was it possible to repeat earlier experiments under vastly different conditions but novel diagnostic techniques were developed and a number of new and surprising observations were made. The literature describing the progress of studies of nonlinear wave processes in ionospheric modification experiments is abundant [Carlson and Duncan, 1977; Stubbe et al, 1982, Stubbe and Kopka, 1983; Djuth, 1985; Duncan, 1985; Stubbe et al, 1985; Thidé, 1985; Erukhimov et al., 1987].

### 3.2.2 Discoveries made at Tromsø

#### i Heater-Enhanced Incoherent Scatter

The main reason for using EISCAT was to measure the state of the unmodified and modified ionosphere and to detect electrostatic plasma waves excited linearly or nonlinearly by the heater. Drawing on earlier experiments of a similar nature at Arecibo, the idea was to utilize the unique possibilities provided by EISCAT, with its tristatic configuration and a location which makes it possible to detect electrostatic waves propagating along the geomagnetic field, to compare the results with older experiments and with existing theories. Also, it was anticipated that new phenomena were likely to be discovered.

The Tromsø Heating experiments have shown that the physics is more complicated than indicated by earlier experiments. Even though we have yet only "scratched the surface", many interesting results have come out of the EISCAT experiments. Some of them are briefly described in the following list:

**1981** First observations of heater-enhanced plasma lines with EISCAT/UHF. A surprisingly pronounced overshoot was observed at heater turn-on (Hagfors et al, 1983).

**1982** Observations with EISCAT/UHF of strong, parametrically excited plasma waves propagating along the geomagnetic field line. Distinct signatures of strong excitation of the oscillating two-stream instability (Kohl et al, 1983).

**1985** Observations with EISCAT UHF indicating that the ionospheric response to a powerful HF wave involves a number of plasma instabilities with vastly different characteristic time scales (Jones et al, 1986).

**1985** First bistatic observations of heater-enhanced ion and plasma lines in EISCAT UHF spectra persisting throughout the whole heating on period of 30s. Simultaneous observation of 145 MHz coherent radar echoes and stimulated electromagnetic HF emissions from the plasma turbulence (Nordling et al, 1988).

**1986** Detection of "extra" components in the EISCAT UHF plasma line spectra during heating experiments. The results indicate the existence of heater induced plasma waves upshifted from the pump frequency by hundreds of kHz. Possibly this is evidence of the existence of "free modes" due to strong turbulence (caviton creation and collapse) (Isham et al, 1989).

#### ii Stimulated Electromagnetic Emission

The first observation of secondary electromagnetic emission stimulated by a powerful HF

radio wave in the ionosphere was made in a very preliminary experiment with the Tromsø heater in August, 1981. The Stimulated Electromagnetic Emission [SEE] was detected by using a long receiving antenna connected to a sensitive spectrum analyser tuned to frequencies near the heater frequency [see figure 3]. Since then a number of discoveries have been made using basically the same technique but with continually improved sensitivity and resolution. Here follows a list of significant break-troughs in SEE experiments with the Tromsø heater:

**1981** First observations of frequency shifted electromagnetic daughter waves stimulated by a strong HF radio wave in the ionospheric plasma (Stubbe et al, 1982; Thidé et al, 1982).

**1981** First observation of SEE under different observations angles ($0^o$ = Tromsø, $20^o$ = Skibotn, $45^o$ = Kiruna) and first evidence of a strong dependence of the SEE components on the polarisation (helicity) of the mother wave (Thidé et al, 1982).

**1981** First detection of a very strong and broad SEE component in the upper sideband for a specially chosen HF pump frequency (Thidé et al, 1983).

**1981** First detection of a close-in sideband component in accordance with the theory of stimulated Brillouin scattering of an HF wave in the ionosphere (Thidé et al, 1983).

**1981** First observation of a distinct, systematic temporal behaviour of the SEE components (Thidé et al, 1983).

**1981** First detection of "main overshoot" in SEE spectra (≈ 200 ms) at turn-on of the HF pump. Similar phenomena also at pump turn-off (Thidé et al, 1983).

**1982** First observation with modulated HF pump of SEE frequency components at the arithmetic mean of the injected carrier frequency and sideband frequencies (Stubbe et al, 1985).

**1983** First observation of stimulated scattering off a low frequency mode with a $k$ vector matched frequency considerably larger than the ion acoustic frequency (Stubbe et al, 1984).

**1983** First observation of a very distinct features with extremely low frequencies (≈ n x 16 Hz, n = $\pm 1, \pm 2$) in SEE spectra (Stubbe et al, 1984).

**1984** First observation of a strong pump frequency dependence of the frequency of the upshifted component near the third and fourth harmonic of the local electron gyro frequency (Leyser, 1989).

**1986** First discovery of harmonic and subharmonic EM components generated by a strong HF wave in the ionosphere. The frequency doubling is attributed to a combination of parametric decay and Raman upconversion. This experiment makes possible the identification of ion-cyclotron waves and, hence, the measurement of ion masses directly from the ground. The emissions on half the pump frequency are caused by either stimulated Raman scattering or, possible, a two-plasmon decay. None of these processes have been observed earlier in the ionosphere (Derblom et al, 1989).

**1988** Identification of SEE spectral signatures caused by relatively small-scale pump induced cavities near the pump standing wave maxima. Makes it possible, for the first time, to estimate the pump field strength in the interaction region by ground-based measurements (Leyser and Thidé, 1988).

**1988** Identification of SEE spectral signatures probably caused by the excitation of electron cyclotron harmonic modes and lower and upper hybrid modes. May provide a method for a high-precision measurement of the local magnetic field strength in the upper hybrid layer a few kilometers below the reflection height (Leyser, 1989).

### iii Heater-Induced Coherent Backscatter

Very soon after the Tromsø heater became operational, backscatter radar experiments, aimed at observing heater-enhanced backscatter cross sections, were performed. Many of the observations made agree reasonably well with earlier observations at Platteville and

elsewhere. However, the scattering volume seems to be larger and the variability higher. Most likely, this is due to the location at Tromsø with its different geomagnetic conditions. Irregularity scale lengths ranging from 1 to 50 m were probed in the following experiments:

**1981** First observation of Tromsø heater-induced backscatter echoes on radars at Uppsala (15.6 MHz), Lycksele (14 and 17 MHz), and Kiruna (3 and 7 MHz). The echoes growth and decay time scales were longer for lower frequencies. The scattering volume was found to extend surprisingly far (40-80 km) below the heater reflection altitude (Hedberg et al, 1983).

**1982** The heater-induced backscatter echoes observed with a 14 MHz radar at Lycksele were found to exhibit a power-law amplitude relation with the heater output power (Hedberg et al, 1986).

**1982** The first observations of 140 MHz plasma line backscatter from Kiruna with an observation angle of approximately $45^{o}$. The echoes were tentatively explained in terms of scattering off Langmuir waves generated by direct conversion of the heater wave due to interactions with striations (Hedberg et al, 1984).

**1983** First observations, with a 49.6 MHz radar, of E-region irregularities generated by the Tromsø heater. The results were found to be strongly dependent on geophysical conditions with, for instance, vastly different e-folding growth times (Djuth et al, 1985).

**1983** Analysis of a large number of STARE radar observations showed that the excitation of heater-induced 1 m irregularities was strongest during magnetic quiet (Kp <3) in the time span from 2100 to 0100 MLT. The irregularities had a preference for overdense 0 mode heating but excitation was observed also under underdense conditions. Even X mode heating could excite irregularities, but this is a rare phenomenon (Hibberd et al., 1983; Høeg et al, 1986).

## 3.3 Active Aeronomical Experiments

### 3.3.1 F Region Irregularities

#### i Short-scale irregularities and anomalous absorption

One of the most unexpected results of the earliest heating experiments at Platteville was discovery of heater induced anomalous absorption of low power diagnostic waves traversing the heated F region. This phenomenon has been studied in great detail at Tromsø [Stubbe et al., 1982a,b; Jones et al.,1982,1984, 1986; Robinson 1983, 1985, 1988, 1989], where it is extremely intense [>10 dB] and easy to excite. It is now accepted that anomalous absorption, which can only be excited by an ordinary-mode heating wave and only affects ordinary-mode test waves, is caused by the conversion of electromagnetic energy into electrostatic wave energy due to the presence of short-scale field aligned irregularities [FAI] in the upper-hybrid resonance region [invariably this is close to the heater wave reflection altitude]. This results in the unstable growth of the FAI, with dimensions of a few metres across the geomagnetic field, through the thermal oscillating two-stream instability [Dysthe et al., 1983; Robinson, 1989]. A new technique for estimating the spatial dimensions of FAI has been developed by workers from the University of Leicester, UK [Robinson 1983,1989; Jones et al., 1984]. This information, together with the decay time constants of FAI, measured by various diagnostic techniques, have enabled good estimates of electron transport coefficients to be determined. This type of experiment is a good example of how active experimentation has been exploited for aeronomical purposes.

#### ii Medium scale irregularities and scintillations

Medium scale irregularities with dimensions of several hundreds of metres to tens of kilometres across the geomagnetic field are a common but not particularly well understood feature of the polar ionosphere. In the natural ionosphere they are associated with both narrow arc-like dynamic features and also with the breakup of larger forms. It is

irregularities of these scale sizes which give rise to scintillation in transionospheric VHF and UHF radio waves and also spread-F phenomena in HF radio and radar systems. The first heater induced medium scale irregularities at Tromsø were detected in radio star scintillation data received passively by the EISCAT UHF radar [Frey et al., 1984]. Further studies were carried out at Tromsø with a purpose built scintillation receiver operating at 250 MHz in conjunction with a polar beacon satellite [Basu et al., 1987]. These experimental observations are in good agreement with the self-focussing theory of medium scale irregularity excitation and have given important new insights into how large scale sources of heat in the ionosphere can become unstable and break up into plasma density striations. Such cascading effects are also thought to play a major role in the generation of naturally occurring irregularities at high latitudes.

#### iii Large-scale heating effects

One of the major findings of the Leicester experiments was the discovery that the heater wave itself suffered strong anomalous absorption. This effect has proved an extremely fruitful source of information concerning strongly nonlinear processes such as wave self-action [Robinson, 1985] and hysteresis [Kopka et al., 1982, Jones et al., 1983, Robinson,1983, 1988, 1989]. In addition, the strong anomalous heating of the electron gas in the vicinity of the heater reflection altitude causes large [~100%] increases in the F region electron temperature on scales comparable with the dimensions of the heater beam [Jones et al., 1986]. The temporal response and the vertical profile of the modified temperature has been measured with aid of the EISCAT UHF radar [Robinson, 1989]. These observations may be explained if it is assumed that the heating occurs in a very narrow height range [<10 km] and that heat is transported along the geomagnetic field lines by electron thermal conduction [see figure 4] EISCAT observations have also revealed the first evidence of heater induced thermal cavitation in the F region. This occurs during intense heating when the temperature gradients in the vicinity of the electron temperature peak are strong enough to expel electrons from the locality, resulting in a detectable depletion in electron density [~10-20%]. The response of the electron density to heating is complicated by the existence of competing effects. For example, temperature dependent reaction rates tend to cause local increases in electron density [at least at altitudes below 250 km], while field aligned diffusion tends to cause depletion. The precise prediction of the electron density response to the heater is still beyond our present understanding of F region chemistry and transport processes. The role of wave induced [anomalous] transport, in particular has yet to be fully explored. Work on this topic is currently in progress at Leicester University.

Large scale electron density changes caused by heating have been detected by several diagnostic instruments other than the EISCAT UHF radar. The first evidence for the dominance of anomalous heating over collisional heating at Tromsø was obtained from observations of phase changes induced in low power HF test waves [Jones et al., 1982]. Recently, Wright et al.,1988 have reported dynasonde observations which indicate the occurrence of large scale heater induced density depletions triggered by the passage of an atmospheric gravity wave through the heated volume.

### 3.3.2 Heating of the Lower Ionosphere

In the collisionally dominated lower ionosphere Ohmic dissipation of the heating wave is the dominant mechanism leading to enhancement of electron temperature [Te]. The time constant is very short, typically 10 μs at 60 km and 1 ms at 90 km with an exponential height dependence, so that Te can be modulated far into the VLF [Very Low Frequency] range. The

electron density [Ne], on the other hand, has a long time constant which decreases with altitude so that a significant electron density modulation is possible only at ULF frequencies [<1 Hz] and at E-region altitudes. Through the dependence of the ionospheric conductivities on Te and Ne, it is possible by amplitude modulating the heater wave to produce at 80 km a roughly 25 km diameter patch of variable conductivity plasma which, in the presence of significant horizontal electric fields, can radiate waves up and down. A large part of the heating work at Tromsø has been devoted to this field, the highlights of which are summarized below [see figure 5].

### i ELF and VLF Wave generation

After the first measurements were reported by Soviet workers [Getmantsev et al, 1977], the first demonstration in the West of signals being produced by modulated ionospheric heating was in Tromsø. By measuring both amplitude and phase it was shown that the signals were of ionospheric origin [Stubbe et al, 1980, 1981; Dowden et al, 1981].

Comparisons of the signals received on the ground directly underneath heated ionosphere with other measurements [chiefly from STARE and magnetometers] showed that both the amplitude and phase can be modulated by large scale electric fields on time scales from seconds to hours [Rietveld et al, 1983, 1987, 1988]. By sweeping the heating beam slowly in the north-south meridian, information on spatial variations of the electric field could also be gained [Rietveld et al, 1984].

Ground measurements made 550 km from the source showed that the radiated power in the frequency range 1-1.5 kHz is typically 1 Watt [Barr et al, 1985], in agreement with theory [Barr and Stubbe, 1984a] for electric fields of a few tens of mV/m and an effective radiated power of 270 MW. ELF/VLF waves were detectable 550 km away from the source with 1 min integration, and have been observed 1000 km away [Barr, work in progress].

Whistler mode signals in the range 1-6 kHz generated by the heater have been detected on 3 separate satellites: on ISIS-1 at 1200 km [James et al, 1984], on Aureole-3 at 1900 km [Lefeuvre et al, 1985] and on DE-1 at 11000 km [Inan and Helliwell, 1985]. This demonstrates that the whistler-mode signals propagate deep into the magnetosphere. A detailed search for signals near the conjugate point [Mawson, Antarctica], however, showed no evidence of the signals. This is probably because ducted whistler-mode propagation, usually necessary for ground reception, is rare outside the plasmapause. Neither have electron precipitation from the magnetosphere as a result of VLF wave-particle interactions, nor triggered emissions ever been observed, probably for the same reason.

Measurement of the VLF harmonics produced by square-wave amplitude modulation gave information on the heating and cooling time constants in the D-region [James, 1985]. Equivalently, measurements of the transient VLF response to a heater-on or heater-off transition gave similar information [Rietveld et al, 1986], which agreed well with numerical modelling.

Using the beam-steering capability [by phasing] of the heater, a directional ELF antenna was produced by heating two ionospheric patches in antiphase separated by half the wavelength corresponding to the modulation frequency [Barr et al, 1987]. This doubled the signal strength at the receiver 550 km away.

Beam steering was used to increase the power efficiency of ELF/VLF generation by a factor

of about three by tilting the beam in the desired propagation direction [Barr et al, 1988]. The signal variation as a function of tilt angle could be well reproduced only by a model which included the sidelobes of the antenna radiation pattern.

Advanced models have been developed which successfully explain many of the characteristics [including frequency dependence and amplitudes] of signals on the ground directly under the heated region [Rietveld et al, 1987, 1989] and at long distances [Barr et al, 1987, 1986].

### ii ULF and lower ELF modulation

Modulation of ionospheric currents at frequencies below a few Hz allows the electron density to be modulated in addition to the collision frequency, thereby allowing much larger modulation currents. These experiments were much more difficult to perform and consequently there are more unanswered questions in this field. Magnetometers on the ground within 50 km of the heater recorded magnetic field perturbations in the Pc 1 to Pc 5 [600s period] range caused by periodic heating [Lotz-Iwen, 1983; Maul, 1989; Rietveld, 1985; Stubbe and Kopka, 1981; Stubbe et al, 1985]. The launching of Alfven waves into the magnetosphere by such perturbations has never been demonstrated experimentally although a search was made for Pc-5 perturbations on GEOS-2, and for Pc-1 waves at the conjugate point, Mawson in Antarctica [Webster et al, 1987].

The magnetic field perturbations measured near the heater were occasionally more than an order of magnitude stronger than expected from theory [Stubbe et al, 1985] and sometimes were measured during relatively quiet times. Sometimes they showed an abrupt onset, suggesting that an instability may be involved. Better diagnostic measurements of ionospheric parameters during such experiments are needed, however, to find the mechanism involved. One other mechanism investigated theoretically by Stecker [1985] involved feedback to the original perturbation by electron precipitation from the magnetosphere, but although not completely excluded, appeared unlikely to explain the observations.

### iii D-Region perturbations

Perturbations to the D-region by the heater have been measured directly by the Partial Reflection Experiment [PRE] [Holt et al, 1985; Stubbe et al, 1985], by their effect on VLF waves [Barr et al, 1984, 1985] and by incoherent scatter radar [Turunen and Turunen, 1985]. Changes in the echo strength of up to 12 dB were observed by a PRE at 2.75 MHz after heater switch-on, with two different time constants. VLF waves from a 12.1 kHz Omega station experienced amplitude and phase changes of 0.1 dB and 0.5 deg. by day and up to 6 dB and 50 deg. after sunset. The backscattered power at 933 MHz from the incoherent scatter radar showed small decreases in echo strength from altitudes of about 75 to 100 km. The VLF, incoherent scatter, and some of the PRE observations can be explained by heating-induced steady enhancements of the electron-neutral collision frequency. The PRE measurements also indicated a slower change, thought to be due to a change in ion chemistry due to electron temperature-dependent reaction rates.

The ability to produce a moveable artificial D-region perturbation by beam tilting was used for testing theories of VLF wave diffraction using Omega and other VLF transmitter signals [Barr et al, 1985].

iv **E-Region modification**

In other E-region modification experiments, plasma waves, which were detected by various radars, have been excited. The results and mechanisms involved have some features in common with those in the F-region which are discussed in greater depth elsewhere. O-mode heating at frequencies below the upper hybrid frequency in the E-region excited meter scale plasma waves perpendicular to the geomagnetic field as detected by the STARE radar with 1 m wavelength [Hibberd et al, 1983; Nielsen and Hibberd 1984; Høeg et al, 1986], and by a mobile radar at 3-m wavelength [Djuth et al, 1985]. These observations are not easily explainable by parametric decay instabilities because of the longer growth times observed [50 ms - several seconds] and because of the large threshold power required. Resonance instabilities [see references in Djuth et al, 1985] may be the dominant process for the lower growth rates observed, but additional processes, such as thermal self-focussing instabilities, may be necessary to explain the relatively slow [ > 1s] growth observed when echoes are weak.

Schlegel et al, 1987, observed enhancements of 16 cm field-aligned plasma waves [enhanced ion-line] using the EISCAT 933 MHz radar. The most likely generation mechanism was direct conversion of the heater wave into Langmuir waves, although other mechanisms, such as the oscillating two-stream instability, could not be excluded. Again the instabilities are essentially the same as those in F-region and are discussed elsewhere.

# 4. FUTURE HEATING RESEARCH AT TROMSØ

Clearly the increasing availability of the VHF radar, in addition to the UHF radar, as a heating diagnostic and the advent of the Superheater offer exciting new possibilities for both the near future and after 1993. It is also anticipated that a wide variety of other diagnostic systems will continue to be deployed in support of the heating experiments. These will include diagnostics which are currently available, such as those discussed in section 3, and also new diagnostics such as the mobile VHF radar [RAPIER] and the proposed UK HF radar to be located at Wick in Scotland. It is neither feasible nor desirable to present a detailed description of all the future potential uses of the high power facility at Tromsø. Outlined below are just a few of the possible extensions of present heating work, together with some new ideas.

**Plasma Physics Experiments**

A multitude of physical processes is excited in high frequency ionospheric modification experiments and these experiments continue to shed new light on nonlinear wave-wave interactions and related phenomena. The Tromsø experiments have clearly demonstrated that there is a wealth of nonlinear space plasma physics that is poorly understood and it is therefore important that this type of research be pursued with improved and refined methods. Such work will be beneficial not only for space plasma physics but for plasma physics as a whole.

The natural next step is to perform more experiments involving simultaneous measurements with different diagnostic tools, such as EISCAT, coherent backscatter radars, and SEE. Recent theoretical models suggested for explaining certain prominent spectral features of the stimulated radiation involve parametric decay instabilities and pump induced density depletions. It is also necessary to include additional effects in the models, such as the presence of geomagnetic field-aligned striations, in order to explain the experimental results.

For example, one should compare the radar backscatter from plasma density striations for the different types of SEE spectra to test the suggested theories.

Recent findings with the EISCAT VHF radar [H.Kohl, *private communication*] seem to indicate that the results are much less erratic than on the UHF but that there are significant differences in the spectral shapes compared to what is normally found in Arecibo. Clearly, further EISCAT VHF diagnostics of the interaction volume are needed.

From both EISCAT and SEE measurements we know that there are many processes that take place on the time scale 1-100 ms after heater turn-on and turn-off. High time resolution measurements of the evolution of SEE for these periods wave have just started. Simultaneous EISCAT and SEE observations would provide data of unprecedented quality, facilitating cross spectral analysis and possible identification of new phenomena. It is well known that electrostatic waves exhibit swelling close to cut-offs, similar to that of an electromagnetic wave in the reflection region. The importance of low group velocity electrostatic waves in generating the SEE could be investigated by measuring the decay times of the stimulated radiation as the pump wave is turned off. The SEE spectral features which depend on weakly damped low group velocity waves would disappear at the slowest rate. Simultaneous EISCAT VHF measurements, with their high signal-to-noise ratio, would provide direct information on HF enhanced plasma turbulence as well as on the background plasma.

It has been proposed [Leyser, 1989] that parametric interaction between upper hybrid and lower hybrid waves excites electromagnetic radiation. The electrostatic waves have large wave vectors essentially perpendicular to the geomagnetic field, which make them difficult to probe by EISCAT. However, with HF and VHF radars looking at large angles to the geomagnetic field it will be possible to investigate the existence of enhanced perpendicular electrostatic wave modes in conjunction with SEE observations. Two radars which are suitable for such studies are the Cornell University Portable Radar Interferometer [CUPRI], which operates at 50 MHz and the Leicester University mobile radar [RAPIER], which operates at 150 MHz. CUPRI, which is presently deployed at Lycksele, has three separate receiving systems with spaced antennas, forming two interferometers, one for azimuthal and one for elevation information of the echo position.

As is well known, the powerful electromagnetic pump wave accelerates electrons to suprathermal energies [Carlson et al, 1982]. The effect of fast electrons, accelerated by the pump or of natural origin, are known to give rise to enhanced natural plasma lines in incoherent scatter radar spectra but their effect on SEE is unexplored. Experiments could be performed during night-time, in conjunction with airglow measurements.

Several years ago it was suggested that the injection of two strong transverse electromagnetic waves could lead to a nonlinear generation of a longitudinal wave at the beat frequency [Kroll et al, 1964; Montgomery, 1965]. With a judicious choice of this frequency, one would be able to create large-amplitude plasma waves. These waves could accelerate particles [Karttunen and Salomaa, 1987] and interact nonlinearly with the plasma to strongly excite a number of secondary nonlinear effects. This way of "doping" the near Earth plasma would facilitate diagnostic measurements of the local plasma properties and would seem ideal for the Tromsø Heating and EISCAT facilities. Such techniques have been discussed from the theoretical point of view by Cerisier et al , 1981, among others, but it has never been used in the auroral plasma.

## Plasma Theory

From a theoretical point of view the physics of ionospheric modification still constitutes a challenging plasma physical problem. Significant progress has been made in explaining specific observations in terms of parametric instabilities and various propagation and conversion mechanisms. However, even for these specific problems the theory is often too simplistic. For instance, it has been possible to explain SEE in terms of parametric interactions, but it is required that linear mode conversion takes place, both from electrostatic waves to electromagnetic waves and from the electromagnetic pump wave to electrostatic waves. It is therefore important to investigate the mode conversion efficiency with respect to, wavelength and the plasma density gradient, to investigate the conditions for efficient electromagnetic wave generation.

Also, the effects of plasma density gradients on the nonlinear interaction between electrostatic waves generating electromagnetic radiation should be studied in general terms. This pertains both to Langmuir and ion-acoustic waves in plasma density cavities caused by the standing pump wave or Langmuir cavitons as well as upper hybrid and lower hybrid waves in geomagnetic field-aligned striations.

Essentially, the analysis carried out so far has been *linear* and does not provide a full theory that can explain the observations both qualitatively and quantitatively. What is lacking is a full *self-consistent nonlinear* theory for general ionospheric RF modification. Theoretical work in this direction, supported by numerical simulation on a super-computer, is underway. For this work to be successful it is essential that the Tromsø heating experiments are pursued so that at all stages theoretical results can be checked against experimental ones.

Theoretical work is now increasingly concentrating on the saturation of the instabilities [ie. on nonlinear theories and sophisticated experiments to confirm or discard the respective theories]. There is a strong trend away from weak turbulence theories [which involve the random phase approximation] towards strong turbulence theories. The major problem at present is the saturation of Langmuir turbulence. A solution to this problem is sought in the framework of the Zakharov equations. Although there are good reasons to regard the Zakharov concept as superior to the weak turbulence concept, the almost absurd situation is that weak turbulence theory easily explains the observed plasma and ion line spectra, whereas the numerical solutions to the Zakharov equations thus far have only reproduced the purely growing mode. On the other hand, weak turbulence theory cannot explain the saturation if the energy input is so high that the cascade sequence should reach down to the plasma frequency.

## Large-scale F Region Heating

A great deal of further experimentation at Tromsø is still required to continue the investigation of large-scale changes to the electron density and temperature produced in the F-region by the effects of high power HF radio waves. The horizontal structure of the heated volume has yet to be fully investigated. This can be achieved by scanning the EISCAT beam over the heated volume. In addition, the vertical electron density and temperature profiles need to be measured at the better height resolution afforded by incoherent scatter alternating codes techniques.

The new heater antenna field which is nearing completion at Tromsø will enable a much narrower beam [7° as opposed to the present 14°] to be transmitted. This will increase the

effective radiated power [ERP] of the MPI heater from around 300 MW up to 1200 MW. With the construction of this 'Superheater' at Tromsø, new experiments to test the increasingly non-linear behavior of the ionosphere at these very high powers will need to be performed. EISCAT will serve as the principal diagnostic for these new experiments but low power HF diagnostics will also enable anomalous absorption and other parameters to be measured.

The EISCAT UHF radar is capable of determining the full three dimensional structures of the electron temperature and plasma density in the heated volume. These measurements will allow the effects of both field aligned and cross field transport processes to be evaluated. These factors are important in understanding the role in the heating process played by horizontal gradients imposed by the finite size of the heater beam. A knowledge of the three dimensional distribution of plasma within the heated volume is vital to our understanding of the interaction processes between the EM wave field of the heater and the ionosphere, since the redistribution of the plasma caused by the heater in turn causes the heater wave field itself to be modified. Knowledge of this feedback process will greatly improve our ability to model theoretically the spatial and temporal structure of large scale heating effects. It is intended to investigate the three dimensional structures of both the $14^{o}$ [standard] and $7^{o}$ [Superheater] beams. In the latter case, the comparatively steeper cross field gradients are expected to play an increasingly important role in the plasma transport processes.

In addition to the EISCAT UHF radar, other diagnostic systems, such as low-power HF waves will have to be deployed to determine the amplitude of heater induced small scale plasma irregularities which give rise to anomalous absorption and anomalous heating. The phase of the diagnostic signals yields information concerning the movement of the electron density during heating. The results of these new measurements will be extremely important to our understanding of the saturation mechanism of the nonlinear instabilities generated by the action of the much higher power EM waves which the superheater is capable of transmitting.

The results of observations of the large-scale response to heating by means of high power radio waves have important implications for aeronomy in the auroral ionosphere. Such experiments provide an excellent opportunity for testing our understanding of ionospheric chemistry, composition and dynamics.

**ELF and VLF wave generation.**

Much has been done already in this field, especially with the Tromsø facility. There have not, however, been any detailed comparisons of the ELF/VLF results with models based on simultaneous EISCAT data of the background ionosphere. Another way of testing the models would be to fly a rocket through the modulated D-region with a VLF receiver on board to measure the profile of the artificially generated ELF/VLF waves.

Although ionospheric heating is not the most efficient way of generating ELF/VLF waves [Barr et al, 1987] it has the advantage of a wide bandwidth. More efficient generation of ELF waves should be possible by using larger heated ionospheric areas through phasing of the antennas. Other ideas to produce large VLF pulses by sweeping the heated region at the VLF phase velocity have not yet been tried.

The efficiency of exciting the whistler-mode in the magnetosphere has not been studied deeply. Some discrepancies exist between simultaneous ground and satellite measurements

of the amplitudes of VLF waves [James et al, 1984]. Further experimental and theoretical work is required here.

**ULF and lower ELF modulation**

In the field of ULF modulation of currents through density modulation, more supporting observations of the background ionosphere and of the temperature and density changes by, for example, EISCAT need to be made in order to quantify the heater induced conductivity changes [Stubbe et al, 1985].

Further experiments during the increasing phase of the solar cycle may have a greater success rate, since the most successful results were obtained in the early days of the heating project [1980-1981] when solar activity was still high.

**D-Region perturbations**

Measurements of the perturbed D-region have only just begun. Changes in ion chemistry caused by electron heating should be investigated in more detail. Simultaneous observations by EISCAT and PRE of the heated D-region are required. In this context, it should be noted that plans exist to upgrade the PRE facility.

There is increasing interest in the VLF technique for mapping localized perturbations caused by lightning-induced electron precipitation [eg. Dowden and Admas, 1989, and references therein] so that the ability to produce D-region perturbations in a controlled way is a valuable and rare asset.

Other techniques to investigate the modified D-region include the wave interaction technique [Fejer, 1970], which has never been applied at Tromsø. The dynasonde [HF radar], also situated in Ramfjordmoen, could be employed for D-region measurements. The effect of enhanced electron-neutral collision frequency on cosmic noise absorption as measured by a riometer has never been found, a null result still not understood. Again, this may be due to the right experiment not having been performed yet.

**E-Region modification**

Wright (1975) published results from Platteville showing sporadic-E apparently being triggered by heating near the F-region critical frequency, which have never been satisfactorily explained. At Tromsø there have been some indications of brief sporadic-E layers detected by the dynasonde during heating experiments. Whether these were natural or heater-induced is not clear, but further experiments to search for this effect are desirable.

It has also been suggested [Trakhtengerts, 1988 and references therein] that RF heating of the night-time E-region could trigger or influence geophysical events like substorms or magnetic pulsations, by changing the integrated E-region conductivity sufficiently. Such experiments have not yet been performed systematically.

In the field of E-region plasma wave excitation, the instabilities involved have not been clearly identified, although several likely instabilities have been found. Artificial excitation of meter-scale irregularities could have practical importance in VHF backscatter communications.

There has been only one published observation of heater enhanced ion-lines from the E-

region, and none of enhanced plasma lines. Furthermore, very few measurements of SEE have been made during E-region heating. The E-region plasma may be more complicated to understand than the F-region plasma because of the different collision processes, but is receiving increased attention theoretically [eg. Stubbe, 1989]. The ability to be able to actively perturb some of the plasma parameters, such as Te, will surely be important in testing the theories.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 The HF Heater as an EISCAT Facility

The MPI heating project has been an outstanding international success and has produced a wealth of exciting new results in the fields of both plasma physics and geophysics. This has been achieved with the collaboration of many scientists, mainly from the EISCAT community itself, who have assembled a wide variety of both conventional and purpose built diagnostic probes with which to undertake heating observations. For most of these participating scientists an extremely strong cross-connection exists between their heating activities and their interests in the corresponding naturally occurring phenomena. For example, those who have studied heater induced short-scale irregularities are also actively investigating naturally occurring **E x B** drift irregularities. Similarly, the workers who have studied artificially excited scintillations are also those at the forefront of geophysical scintillation research. From this point of view heating both supports and supplements a broad range of studies in the fields of aeronomy and space physics. Moreover, heating experiments have motivated a substantial amount of new theoretical work, particularly in the area of anomalous absorption and transport, and also in the field of nonlinear dynamics[eg Mjølhus, 1985; Robinson 1983,1989]. However, there is still a substantial amount of heating research to be carried out. This situation will be substantially unchanged after 1993. This is partly because of the present limitations of both manpower and access to time on essential diagnostic facilities such as the EISCAT UHF and VHF radars. In addition, it is inevitable that new and unexpected results will lead to the need for further exploration. It is the firm belief of the Heating Working Group that the best way of fully exploiting the potential of the MPI HF high power facility at Tromsø and the expertise which has already been accumulated within the EISCAT community in relation to heating research, is for the EISCAT Scientific Association to take over the facility from the beginning of 1993. A number of key points are worth considering in this regard:

1. *The EISCAT UHF and VHF radars, together with the HF high power facility, would constitute the single most sophisticated assembly of ground based diagnostics for ionospheric research anywhere in the world.*

2. *The ionosphere above Tromsø is a unique environment for heating experiments because of both its proximity to the auroral electrojet location and because of the near vertical geomagnetic field geometry. This allows active experimentation with both the auroral current system and field aligned transport processes.*

3. *EISCAT would be gaining a mature, reliable and highly desirable facility at relatively low cost.*

4. *Heating experiments have both plasma physical and aeronomical applications and would attract major collaborations between scientists from both inside and outside the*

*EISCAT community. In addition, it is likely that a wide variety of other diagnostic facilities would be attracted to Tromsø to work with the EISCAT UHF and VHF radars.*

*5. Heating experiments offer a unique challenge to the experimentalist and theorist alike. New diagnostic techniques need to be developed which will tax the radar systems to the full extent of their temporal and spatial resolution, in order to fully explore heating phenomena, Likewise, new nonlinear theories are required to explain observations which are so far only poorly understood.*

*6. There remains a wealth of new heating science to be investigated, which probably could be undertaken at no other facility, either now or in the foreseeable future. This will remain the case well after 1993. If heating at Tromsø ceases after 1993 the opportunity to undertake some of the most exciting ground based space physics may be lost for ever.*

If the proposed takeover of the heating facility is given the go-ahead at Council a number of actions would need to be taken on a fairly short time-scale. More details are necessary concerning (a) the precise arrangements for hand-over by MPI, (b) the requirements for equipment and peripheral facilities such as buildings and (c) the schedule for staff recruitment and training. It is suggested that a senior scientist from EISCAT [either a current staff member or a new appointment] should be given special responsibility for carrying out these essential next steps, which need to be completed by the beginning of 1992 at the very latest.

### 5.2 Anticipated Future Use by EISCAT Scientists

A major contribution has already been made to the heating project at Tromsø by scientists from within the present EISCAT community. Those who have been most active have been from Germany, Sweden, U.K. and from the EISCAT organization itself. However, important contributions, both by direct involvement or otherwise, have also been made by scientists from the other EISCAT countries as well as from outside EISCAT [eg. USA and USSR]. Scientists who are currently the most active in the heating project [Germany, Sweden,U.K.] have all expressed strong commitment to the continuation of the programme, preferably under the new arrangement proposed above. Strong support for the continuation of the heating facility at Tromsø has also been received from Norway and France.

### 5.3 Scheduling of EISCAT Heating Experiments

The ideal scenario for takeover would be that the HF heater would become the third major EISCAT facility after the UHF and VHF radars. It is then envisaged that the HF high power facility would become available to any scientist or team of scientists for operation in special programs in exactly the same way as the UHF and VHF facilities are at present. The takeup rate for the HF facility would then be a matter for the individual EISCAT members to decide, through their present procedures for assessing the scientific quality and technical feasibility of proposals for special programme time. It is envisaged that a small team of scientists from the EISCAT staff, who would have responsibility for the heating experiments, should also vet heating proposals. A small steering committee of scientists from the EISCAT community who have special knowledge of heating research could also assist in this vetting procedure.

There is also the question of how time on the heater should be charged to users. The present Heating Working Group recommends that time on the heater be charged in a similar way to that for UHF and VHF use. Thus when experiments involving either the VHF or the UHF radars, together with the heater, are being run it may be felt necessary to charge for time on both (heater and radar) systems separately.

A further point should also be noted: it has been the experience of those who have worked on heating experiments at Tromsø, in the past, that it is quite feasible and often very efficient to run the heater to satisfy several scientific requirements with one well designed experiment. This greatly facilitates and encourages collaboration between different research groups. It is anticipated that such collaborations would flourish even more with the increased accessibility to heating experimentation that EISCAT's takeover of the heater would bring. Collaboration between scientists from different EISCAT countries would certainly make agreements with regard to scheduling heating experiments much easier. The Heating Working Group strongly recommends that collaborative heating experiments should be fostered by EISCAT and that scientists who have not yet been involved in heating research, but who have developed special scientific and technical skills in the use of the EISCAT radars, should be encouraged to take part in such collaborations in the future.

## 6. ACKNOWLEDGEMENTS

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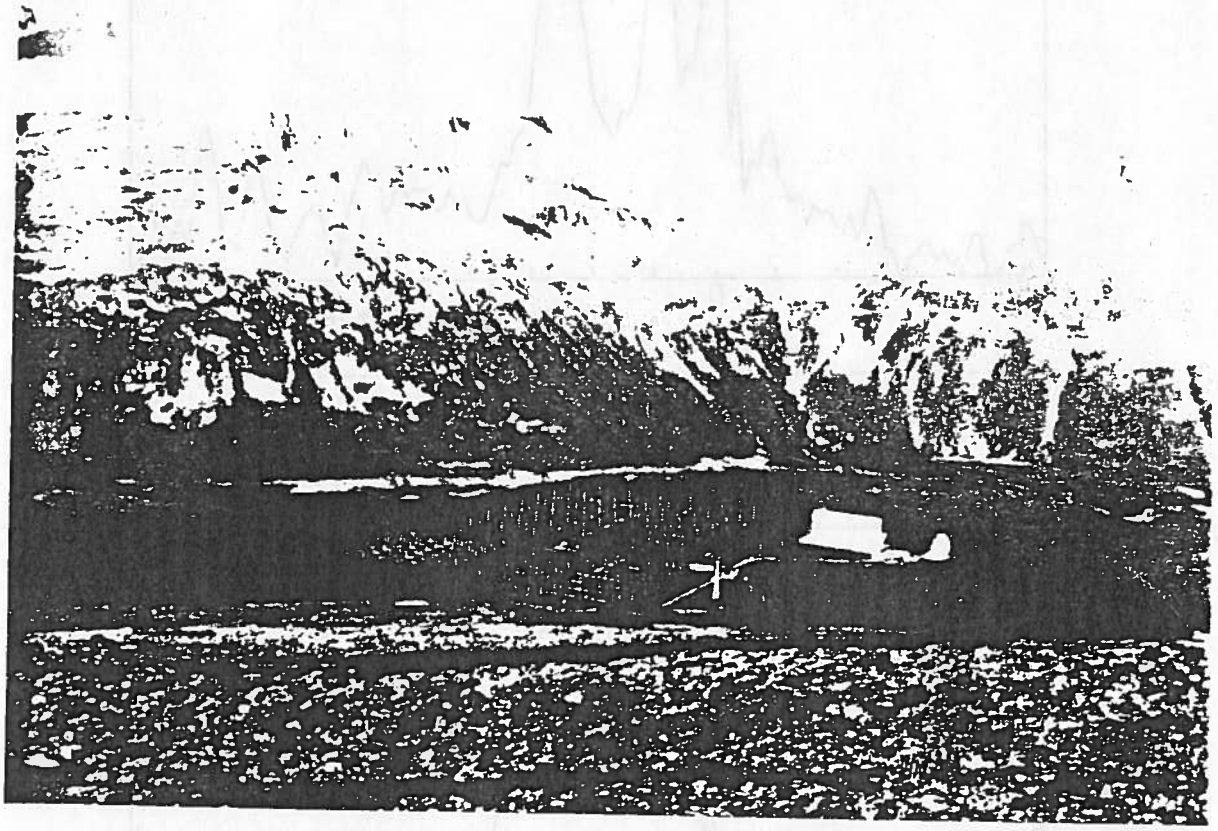

Fig. 1. The EISCAT site at Ramfjordmoen, Tromsø, Norway.

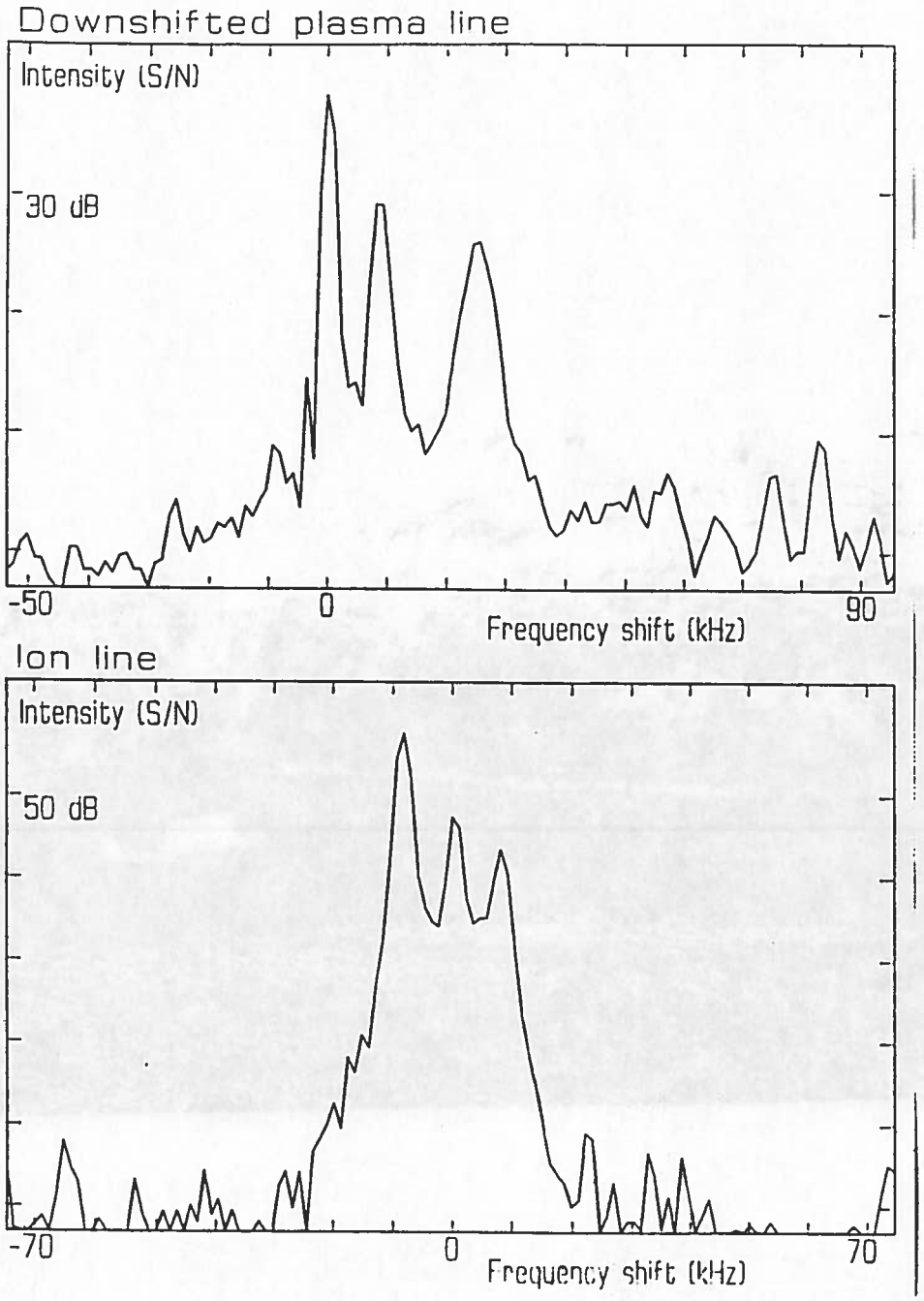


Fig. 2. EISCAT UHF plasma line [upper panel] and ion line [lower panel] during heating. The plasma line exhibits three peaks; one, at zero shift corresponds to the oscillating two-stream instability [OTSI]; another, shifted by 10 kHz corresponds to the parametric decay line; and the third is the first cascade. The ion line also exhibits three peaks. The centre line is caused by the OTSI and the two outer peaks by the decay instability.

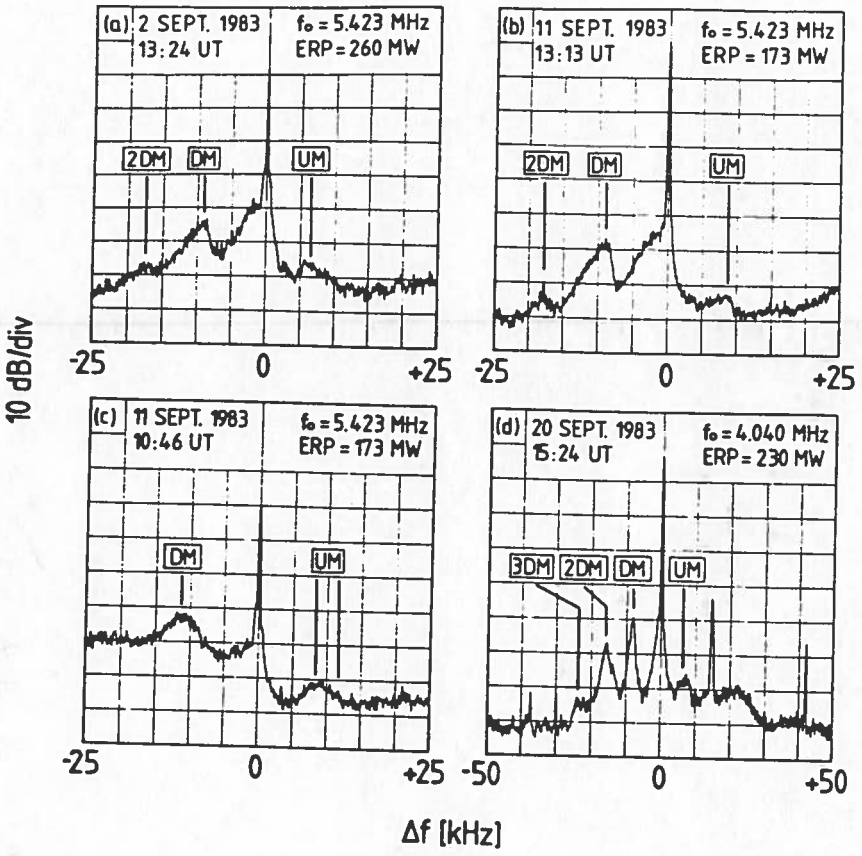


Fig. 3. Four examples of richly structured stimulated electromagnetic emission [SEE] spectra.

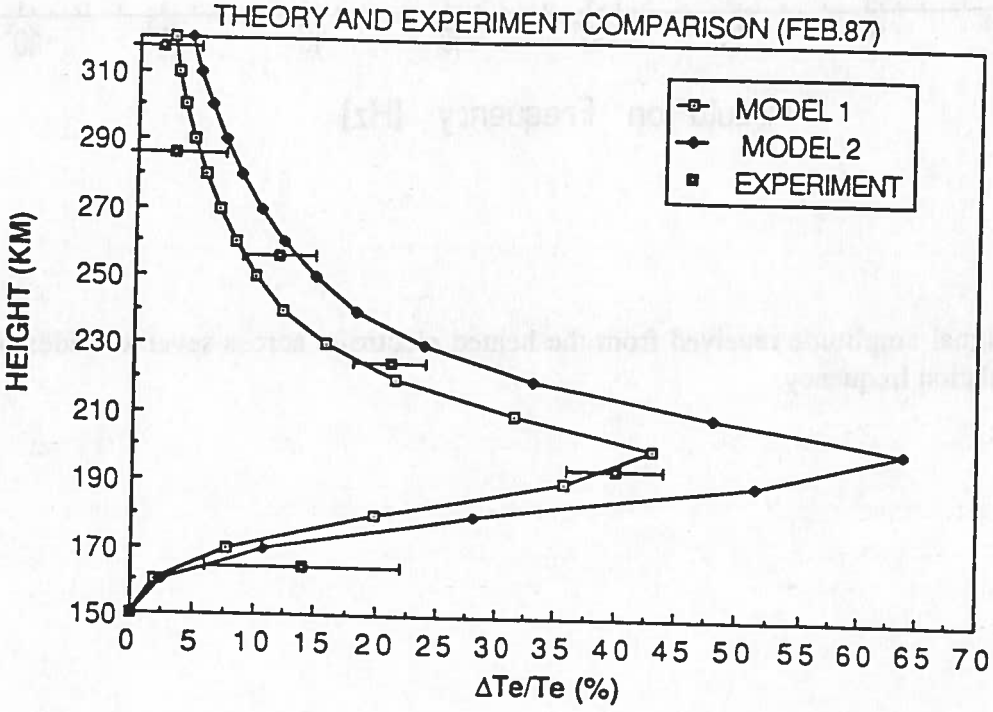


Fig. 4. EISCAT observations of the vertical profile of heater induced electron temperature enhancements, with two theoretical models for comparison.

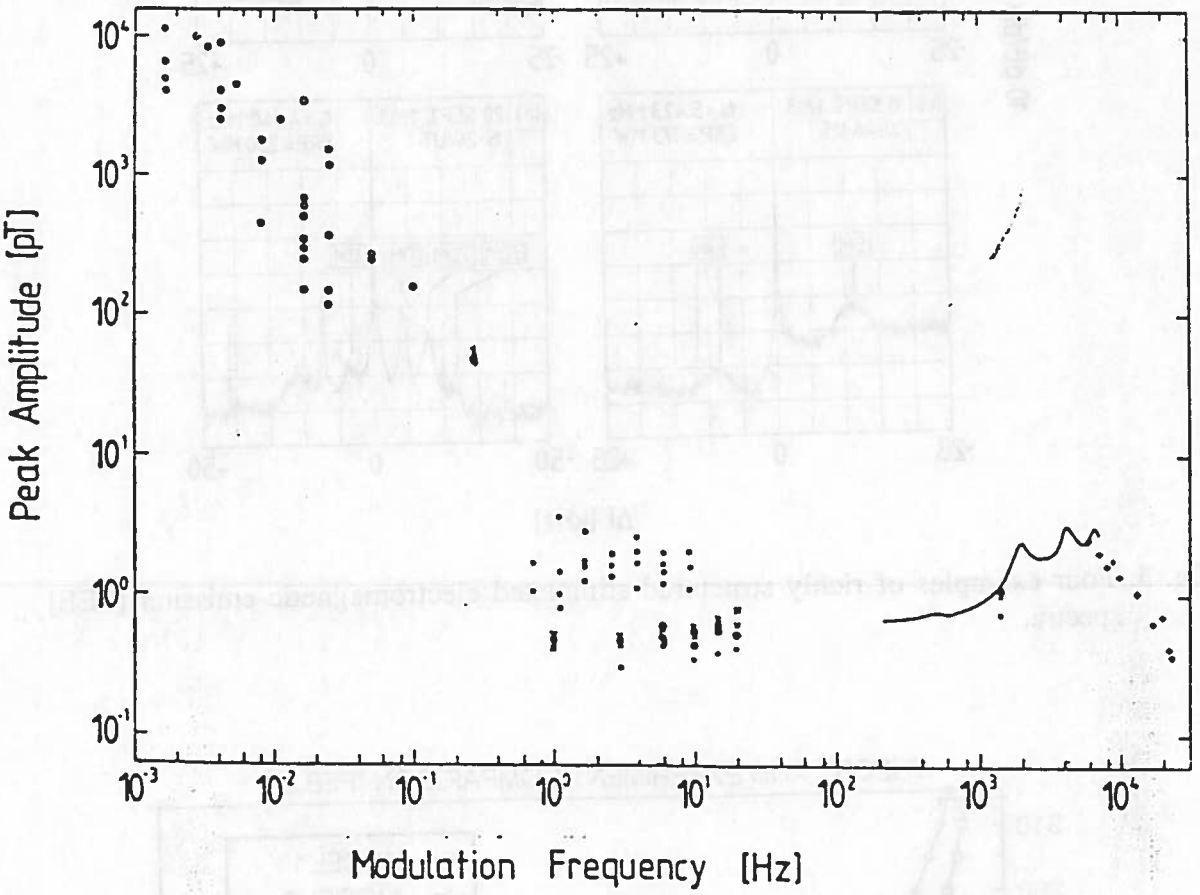


Fig. 5 The signal amplitude received from the heated electrojet across seven decades of modulation frequency.