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What Can We Learn About the Ionosphere Using the EISCAT Heating Facility?

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ABSTRACT

Apart from being used for plasma physics, the HF facility near Tromsø, Norway, can be used to perturb the ionosphere at various heights in different ways, thereby giving information about the ionosphere. The co-located incoherent scatter radars are probably the most powerful instrument for probing the ionosphere, but HF techniques can complement the radars and even have some advantages. The principal perturbation method is to increase the electron temperature in a controlled way, some examples of which are presented here.

Artificial electron heating in the E and F regions is useful for testing aeronomical models. More recently it has been discovered that electron heating can dramatically affect polar mesospheric echoes observed by VHF and UHF radars. Particularly the overshoot effect promises to be a powerful diagnostic of the physics and chemistry related to the formation of these layers, which are thought to involve dust, ice particles and aerosols.

Radio induced optical emissions provide a way of measuring the lifetimes of excited species at different heights in the ionosphere, thereby providing a way of measuring the neutral density which is one of the most important parameters determining the lifetime.

The technique of creating artificial periodic irregularities set up in the standing wave pattern of the up-going and ionospherically reflected HF wave provides valuable information all heights below reflection. One particular feature of this method is that it can detect the presence of layers around 50 km and measure vertical winds, and electron densities and temperatures at various heights.

1.0 INTRODUCTION

Dedicated powerful HF radio wave transmitting facilities have been in use since the 1970s to do both plasma physics and geophysical research. At present there are five operating facilities: HIPAS [1] and HAARP [2] in Alaska, Heating in northern Norway [3], SPEAR on the island if Spitsbergen [4] and SURA in Russia [5]. Another important facility in Puerto Rico [6] was damaged by a hurricane in 1996 but there are plans to build a replacement. Although incoherent radar, which is often co-located with such a powerful HF facility, is recognised as being the most powerful technique for measuring ionospheric and to some extent atmospheric properties, its capabilities can often be extended by using ionospheric perturbation techniques. HF-modification facilities, which themselves are much less expensive than incoherent scatter radars, can also be used together with even less expensive HF or VHF coherent scatter radars or other diagnostics to probe the ionosphere and even magnetosphere as will be shown below.

By perturbing the ionosphere in a controlled way and measuring the effect with some other instrument, it is possible to learn something about the properties of the ionospheric plasma or the neutral atmosphere.

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There are several ways of causing a perturbation with a powerful HF radio wave. The absorption of the wave causes electron heating, which is perhaps the most direct way, and will be discussed in section 2. Another way is to directly excite plasma waves which are localised in their source height by resonance conditions. If the plasma waves are Langmuir or ion acoustic waves they can be measured by incoherent scatter radars and allow accurate calibration of electron densities and temperatures. The associated plasma turbulence can also energize electrons such that they cause the atmospheric molecules to emit light. These plasma wave effects are discussed in Section 3. Modulated electron heating can be used to create low frequency ionospheric currents which are in turn useful for studying the properties of the ionosphere or the coupled ionosphere-magnetosphere system, as discussed in Section 4. Heating effects can also be used to track the ionospheric electric field of naturally-occurring ULF waves, as demonstrated in the same section. Finally, in Section 5 a technique is described where periodic irregularities set up in the standing wave of the reflected HF pump are used as a tracer for ionospheric parameters from the F region down to extremely low heights like 50 km.

2.0 ELECTRON HEATING

A powerful HF is absorbed in the D region through collisions or simple Ohmic heating. Models predict temperature enhancements up to many hundreds or even thousands of degrees, but direct measurements of this by means of incoherent scatter radar has proved impossible to verify so far. Nevertheless the effects of electron heating at heights between about 60 and 90 km are evident. Examples are the modulation of the electron collision frequency and hence conductivities and electric currents by amplitude modulated heating at frequencies from sub-Herz to kHz, as described in Section 4. Heating effects in the E region also exist but have also been difficult to measure [7]. Heating effects in the F region can be strong through anomalous absorption of the HF wave caused by electrostatic instabilities, and have been well documented [8, 9]. We now discuss the diagnostic applications of D region and F region heating.

2.1 The effect of electron heating on the mesosphere

The mesosphere is that region of the atmosphere between about 50 and 85 km where the temperature decreases with altitude and reaches a minimum at around 85 km. It is difficult to access this region except through sounding rockets or radars. Radar echoes require sufficient electron density which is provided through ionising sunlight, precipitating energetic electrons through magnetospheric acceleration processes such as that associated with the aurora, or protons during energetic solar eruptions. When there are sufficient electrons, they can be structured on various spatial scales by turbulence, or by attachment to aerosols such as ice and dust particles, thereby acting as passive tracers of the neutral atmosphere and its inhomogeneities. VHF and occasionally UHF radar echoes which are seen commonly in the polar mesosphere at heights from 80 to 90 km, known as Polar Mesospheric Summer Echoes (PMSE) [10, 11] are still not understood. Weaker and rarer echoes are also seen from lower heights around 70 km, sometimes termed Polar Mesosphere Winter Echoes (PMWE) [12].

Chilson et al. [13] found that the strength of PMSE echoes could be weakened by up to 10 dB by transmitting a powerful HF wave of several hundred MW effective radiated power (ERP). The response time was practically instantaneous [14] suggesting that electron heating, which has a time constant of tens to hundreds of microseconds in these heights [15], caused the weaker echoes. The weakening of the echoes is caused by the increased diffusivity of the hotter electrons smearing out the small (meter) scale structuring of the electrons [16]. More recently O. Havnes predicted that that by using a lower duty cycle modulation, it should also be possible to enhance the strength of the echoes [17]. The effect which was immediately found [18] and which is shown in Fig.1, promises to be an important diagnostic of the mesosphere and D region. This is because, as Fig. 2 shows, the overshoot characteristic curve depends on the aerosol size used in the model. Figure 2 shows two cases computed for a plasma density $n_0 = 4 \times 10^9$ m^{-3} and an increase in the electron temperature from 150 K without heating, to 390 K with heating. The level of suppression (0 to 1 in Fig.2) depends on the temperature enhancement. Two different dust sizes were used in the figure. The dust density is $n_d = 10^9$ m^{-3} for the case with particles of radius r = 10 nm (solid line) and $n_d = 4 \times 10^7$ m^{-3} for the 50 nm large particles (dashed line).

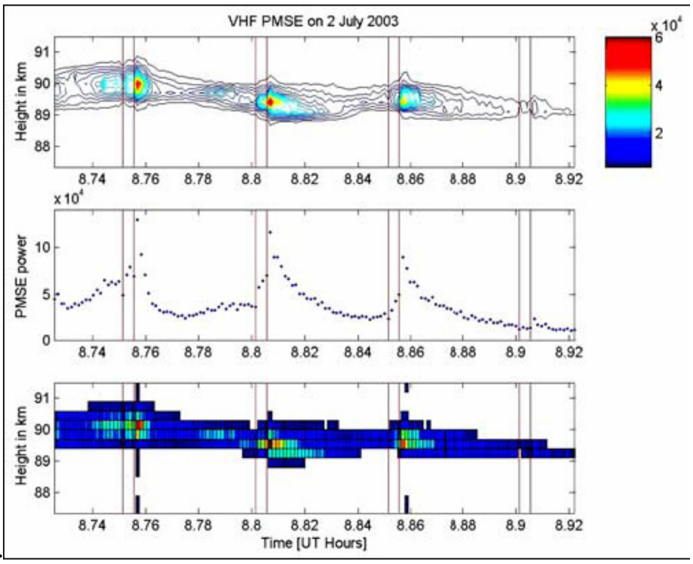

Figure 1: PMSE echo strength showing an overshoot immediately after switch the 3s long heater pulse off. HF on is shown by the vertical lines. The bottom panel shows the raw data, corrected for radar transmitter power, while the upper panel shows the same data but now smoothed. The relative intensity scale is the same for both panels, and the background noise on this linear scale is at approximately 2500. The middle panel shows the sum of the three highest intensities at each time sample and is a measure of the total PMSE intensity as a function of time. Taken from [18].

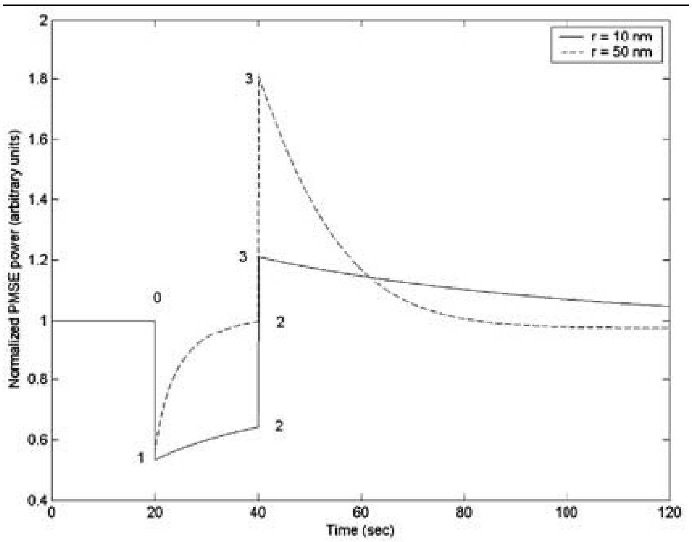

Figure 2: Model calculations showing how the shape of the overshoot phenomenon depends on particle size. HF is on from 20 to 40 s and the amplitude from 0 to 1 depends on the electron heating. Taken from [18].

2.2 Heating effects in the F region

Measurements of HF-induced electron heating in the F-region were first analysed in detail by Mantas et al. [8]. Such measurements provide useful tests of models of the thermal balance of the electron and ion gas in the ionosphere. If one neglects particle concentration changes then only the coupled time-dependent heat equations for the electron and ion gas need to be solved. A large error in the assumed electron energy loss rates through the various collision mechanisms can be detected by comparing the observed with the calculated decay rate of the enhanced electron temperature profile after turning the HF wave off [8].

2.2.1 Artificial optical emissions

Artificial optical emissions from the F region (and E region) can be induced by high power radio waves. The easiest emission to be observed is the red line at 630 nm from $O(^1D)$ which has an excitation threshold energy of 1.97 eV , followed by the green line at 577.7 nm from $O(^1S)$ with an effective energy threshold of 4.19 eV but lines have also been observed at 844.6 nm, from $O(3p^3P)$ with threshold of 10.99 eV and at 427.8 nm with threshold 18 eV from N_2^+ [19]. There seem to be two mechanisms involved. The first is the reasonably well understood thermal heating of the electrons causing the Maxwellian tail to be enhanced [8]. With electron heating of 2000-4000K this mechanism can explain the 630 nm red-line emission of atomic oxygen which has the lowest excitation energy. The other mechanism, which is not well understood, is the acceleration of thermal electrons to supra-thermal energies of up to a few tens of eV by a process involving plasma waves. This second mechanism seems necessary to explain the green line atomic oxygen emission and other emissions with higher energy thresholds.

Whatever the mechanism, it is possible to create a cloud of excited atomic oxygen atoms which can be used to determine thermospheric properties as described by [20]. For example, steady state heating causes the cloud of optical emission to move with the plasma velocity ($\mathbf{E} \times \mathbf{B}$ drift) and show the irregularity structure of the plasma. When the radio wave is turned off, the cloud expands by neutral diffusion drifts and drifts with the neutral wind velocity as the intensity decays on a timescale of tens of seconds. The decay rate is determined by the collisional quenching rate and both diffusion quenching rates are directly related to the atomic and molecular concentrations in the thermosphere. Whereas the neutral wind probably does not vary much with height, the neutral density decreases with height causing the lifetime of the excited O state and the diffusion rate to decrease with height. Thus by measuring the decay of artificial red line emissions at different heights one could obtain a height profile of the neutral density. Some initial measurements which could be used in an attempt to do this is shown in Figure 3, taken from [21], where the optical emission height increased as the ionosphere decayed after sunset. In such experiments it is necessary to determine the height of the optical emissions by triangulation using several cameras. The source height of the electron heating or electron acceleration, which is the upper-hybrid resonance height which is close to but below the HF reflection height, can usually be determined from ionosonde or radar measurements.

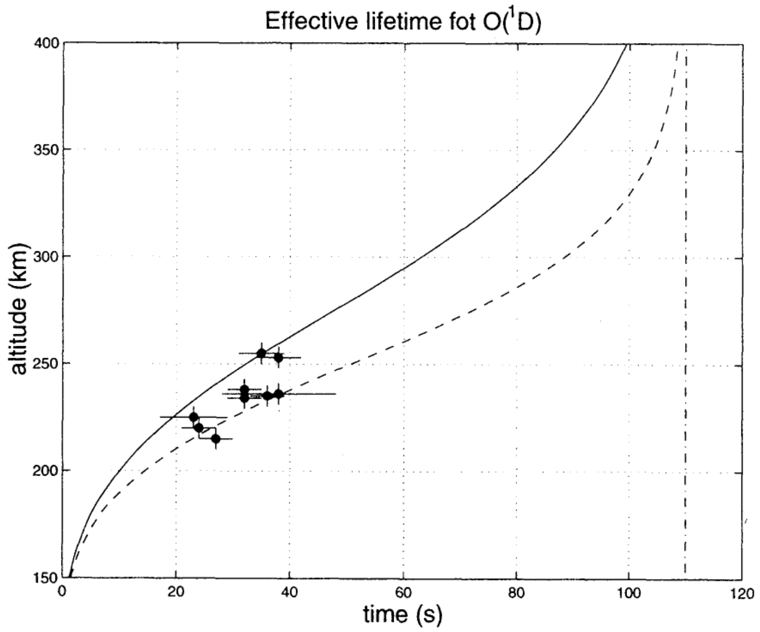

Figure 3: Altitude variation of the decay time constants of O(^{1}D) from [24]. The dot-dashed line shows the radiative lifetime of O(^{1}D), the dashed curve including quenching by O_2, N_2 and ambient electrons, the solid curve including quenching by atomic oxygen. The markers show estimates of the time constant from the experiment described in [21].

3.0 PLASMA WAVE EXCITATION

The electric field of the powerful HF wave becomes even stronger near the reflection height as a result of the decreasing refractive index. It can decay into ion acoustic and Langmuir waves both of which may be detected by incoherent scatter radars and thereby provide a strong signal, in a usually very narrow range extent which is ideal for calibrating electron density measurement of such radars. Often it is even possible to obtain such enhanced ion and plasma lines on the topside ionosphere, through tunnelling of the HF wave in the Z-mode [Isham ?].

4.0 ULF, ELF, VLF WAVE EXCITATION AND DETECTION

4.1 Excitation of ELF/VLF waves

The production of ELF/VLF waves (from hundreds of Hz to many kHz) by modulated heating and thereby conductivity modulation in the lower layers of the ionosphere allows a number of diagnostic techniques. An advantage of this source of low frequency waves is its wide instantaneous bandwidth in spite of the low efficiency [22]. One approach is to use the radiated ELF/VLF waves propagating in the Earth-ionosphere waveguide to test models of propagation and models of the lower ionosphere, as done by Barr et al. for example [23].

The nonlinear relationship between electron temperature enhancement and HF energy input depends on the loss mechanism of the heated electrons. For small electron temperature enhancements, rotational excitation of N_2 and O_2 is the most efficient energy loss mechanism. Its temperature dependence is known to be $(T_e - T_n)/T_e^{1/2}$ where T_e and T_n are the electron and neutral temperatures respectively Since the collision frequency ν_e is approximately proportional to T_e, there exists an altitude above which the HF absorption coefficient increases with T_e more strongly than $T_e^{1/2}$ It is obvious that in this case there is a critical energy input above which the loss cannot compensate the gain. Correspondingly, a runaway solution for T_e arises, which is eventually limited by other energy loss mechanisms, mainly vibrational excitation of N_2 and O_2. This relationship could be measured by seeing how the amplitude of waves at a fixed ELF/VLF modulation frequency having a fixed modulation depth varies as the average HF level is increased, as outlined in [24]. Although there have been many ELF/VLF modulation experiments performed over the years, this particular one has not been done, but it could provide the shape of the T_e vs. HF-power curve which one should be able to relate to the model containing the height profile of $[O_2]$,$[N_2]$ and T_n.

4.2 Excitation of ULF waves

The production of ULF waves below about 10 Hz is particularly interesting because there are so few alternative artificial sources. These waves, as they propagate into the magnetosphere as Alfvén waves can be very efficiently guided along the magnetic field to satellites and thereby provide a tracer of the field line [25, 26] They may also be used to actively study the ionospheric Alfvén resonator. [27, 28, 29].

4.3 Detection of ULF waves using heating

There are at least two ways of detecting the ionospheric signature of naturally occurring ULF pulsations. The first way is by the fact that the electric field of the natural ULF wave modulates the current system in the lower ionosphere thereby imparting its frequency on any ELF or VLF waves that may be produced by artificial modulation of those currents. Signatures of natural Pc 4 and Pc 1 ULF waves were thus found on ELF/VLF waves produced by the HF facility and recorded on the ground nearby [30, 31]. These ULF waves were also seen by ground-based magnetometers.

Another, more interesting technique can be used to detect the ionospheric signature in the F region of pulsations that have such a localised spatial scale that they are not normally observable by ground based magnetometers because of the shielding effect of the ionosphere. It involves generating decameter scale irregularities near the upper-hybrid resonance height using o-mode heating, and then detecting the movement of the irregularities with coherent radars like SUPER DARN as shown in [32]. The horizontal electric fields of the pulsation cause an $\mathbf{E} \times \mathbf{B}$ force on the plasma containing the artificial irregularities resulting in a Doppler shift of coherently scattered radar signals. The artificial irregularities have a very narrow intrinsic backscatter spectrum [33], allowing high precision measurements of the drifts.

5.0 PROBING OF ARTIFICIAL PERIODIC IRREGULARITIES

A particularly powerful method of using heating facilities to probe the ionosphere from the reflection height of the HF wave down to 50 km or so is the artificial periodic irregularity (API) technique developed by a Russian group using the SURA HF facility [34]. The technique relies on the standing wave pattern created by the by the HF wave and its reflection causing a horizontally stratified periodic perturbation to the refractive index which is then probed by pulsed HF radio waves matching the Bragg scattering criterion. This probing can be performed with the same frequency and polarisation as the pump wave so that the Bragg condition is met at all heights. In this case the probing can only be done to watch the irregularity pattern decay immediately after the pump switches off. Alternatively, the probing can be done with another frequency and polarization such that the Bragg condition is met over a narrow range of heights, but while the pump wave is on. The first mode is appropriate for D region heights where the time constant for irregularities to decay is generally long enough. An example is shown in Fig. 4 where irregularities are formed in two height regions, 80-100 km and 50-60 km and decay with different time constants which are determined by the ion chemistry [35].

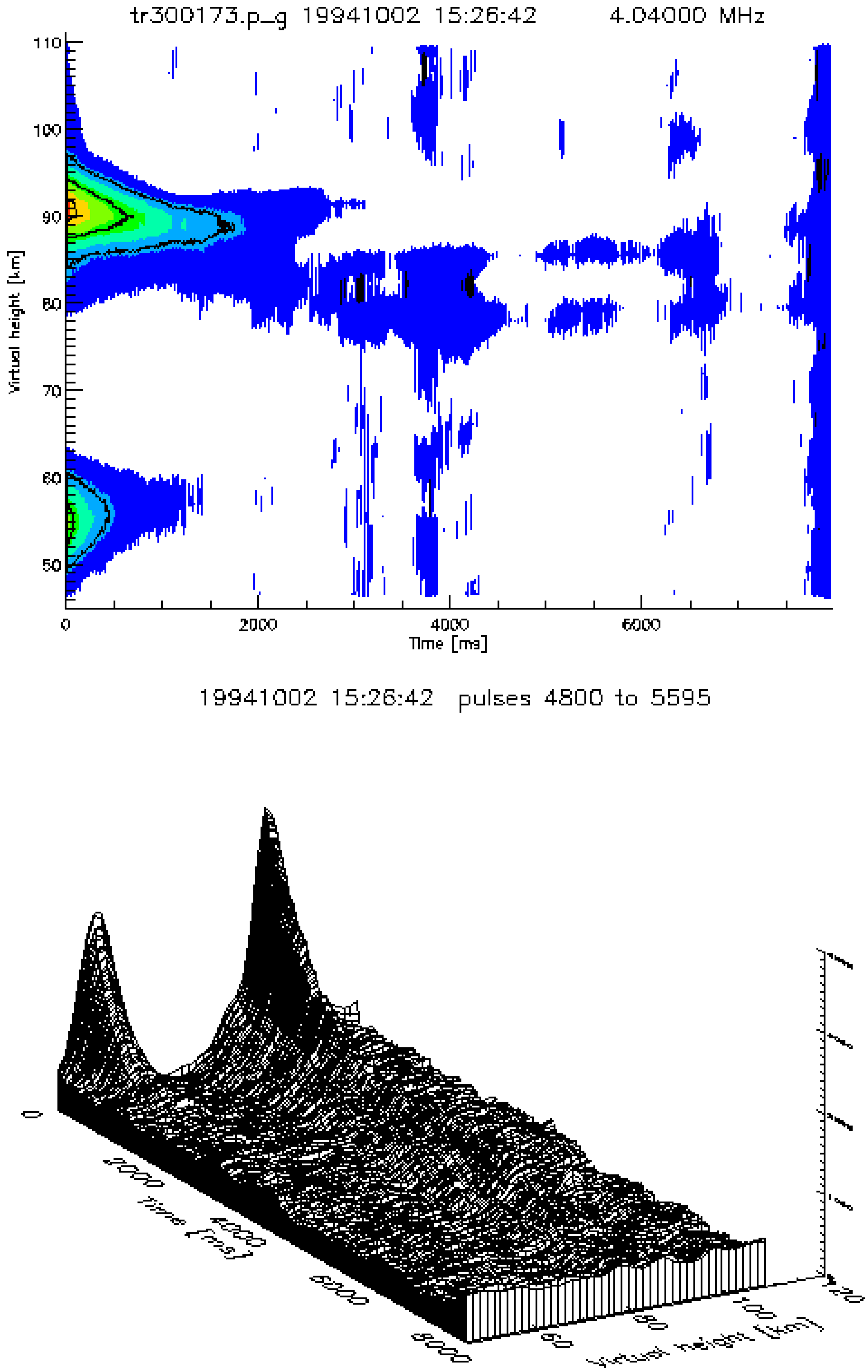

Figure 4: Very low altitude echoes from decaying irregularities after turning off the standing

wave pattern caused by the powerful HF wave and its ionospheric reflection.

6.0 SUMMARY

I have presented some examples of HF-heating of the ionosphere can be used to learn about the ionosphere and even magnetosphere. Most of the techniques have been tried to some extent, but there is a large potential to exploit them in a more systematic way.

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