Model for artificial ionospheric duct formation due to HF heating


Model agrees well with the observations, and provides ionospheric plasma density perturbations that stretch along the magnetic field lines. Those density perturbations can serve as ducts for guiding natural and artificial ELF/VLF waves. This paper presents a theoretical model of duct formation due to HF heating of the ionosphere. The model is based on the modified SAMI2 code, and is validated by comparison with two well documented experiments. One experiment, conducted at the SURA heating facility, used the low orbit satellite DEMETER as a diagnostic tool to measure the electron and ion temperature and density along the overlying satellite orbit close to the magnetic zenith of the HF-heater. The second experiment, conducted at the EISCAT HF facility and diagnosed by the EISCAT Incoherent Scatter Radar, measured the vertical profiles of the electron and ion temperature between 150–600 km. The model agrees well with the observations, and provides a new understanding of the processes during ionospheric modification. Citation: Milikh, G. M., A. G. Demekhov, K. Papadopoulos, A. Vartanyan, J. D. Huba, and G. Joyce (2010), Model for artificial ionospheric duct formation due to HF heating, Geophys. Res. Lett., 37, LXXXXX, doi:10.1029/2010GL042684.

1. Introduction

It is well known that the presence of field aligned density structures plays a critical role in the propagation of whistler waves in the ionosphere. The density structures serve as ducts for VLF/ELF waves since the density gradient perpendicular to the magnetic field line can lead to their total internal reflection [Streltsov et al., 2006]. Such density structures have often been observed [Carpenter et al., 2002] to extend over distances covering entire magnetic field lines. They are known to trap and guide whistler-mode waves between conjugate regions [Koons, 1989].

The possibility for creating such trans-hemispheric ducts artificially was discussed by Perrine et al. [2006], where a 1D model which simulates the plasma along an entire magnetic dipole field line was used. It was shown that long term continuous HF heating of the F-region by powerful ionospheric heaters, such as HAARP, generates a strong thermal wave in the ionospheric and magnetospheric plasma.

The thermal wave propagates along the magnetic field line through the topside ionosphere and magnetosphere, driving ion outflows, displacing the ambient plasma and leading to the formation of density ducts that stretch along the magnetic field line to the conjugate point. We have recently generalized the previous 1D computational model to a 2D model by incorporating simulations of the plasma in the latitudinal direction. The new model allows one to describe the ionospheric parameters in both vertical and latitudinal directions with much better resolution than the old one. Therefore the new model allows for close and useful comparisons with data obtained by radars and satellites that the old model does not allow. The key objective of this paper is to validate this new model based on SAMI2. To accomplish this we will check the model against two recent well diagnosed experiments which detected large scale ducts caused by the HF heating. One experiment was conducted at the SURA heating facility and used the low orbit satellite DEMETER [Berthelier et al., 2006a, 2006b] as a diagnostic tool [Frolov et al., 2008] to measure the electron and ion temperature and density along the satellite orbit close to the magnetic zenith of the HF-heater. Another heating experiment, conducted at the EISCAT HF facility and diagnosed by the EISCAT Incoherent Scatter Radar (ISR) [Rietveld et al., 2003], measured the vertical profiles of the electron and ion temperature between 150–600 km.

The letter is organized as following: the next section describes the numerical model applied. In the discussion section the model output is compared with the EISCAT radar and DEMETER observations followed by conclusions.

2. Numerical Model of Formation of the Artificial Ducts

The theoretical/computational model is based on the SAMI2 code developed at the Naval Research Laboratory [Huba et al., 2000]. The code is a Eulerian grid-based code, which describes an ionosphere made up of seven ion species. The equations of continuity and momentum are solved for the electrons and each ion species, with the temperature equation solved for the electrons and H+, He+, and O+ species. The electron density is determined on the basis of charge neutrality. The code includes E × B drift of the field lines with frozen-in plasma (in altitude and longitude), an empirical neutral atmosphere model, horizontal winds, photo-deposition into the ionosphere, ion chemistry models, and ion inertia. This inclusion of ion inertia is critical since it allows for the study of sound wave propagation in the plasma. The SAMI2 model is inter-hemispheric and can simulate the plasma along the entire dipole magnetic field line (for the geometry of the model see Perrine et al. [2006]). The most recent version of the SAMI2 code (release 0.98) which allows description of processes at high latitudes was used here. HF heating of the ionosphere is a complex phenomenon.
It begins with the HF absorption which pumps the ionospheric turbulence that in turn generates the plasma heating [Gurevich et al., 1996; Gustavsson et al., 2001]. Since the SAM12 code does not consider wave propagation and absorption we introduced in the model a flexible source of electron heating, as we did it in an earlier paper by Perrine et al. [2006]. This source of the electron heating was presented in the form of localized heating rate per electron

\[ q = \frac{\mu P}{V_{th}} f(x, z) = 260 \mu P(MW) \left( \frac{10km}{a} \right)^2 \left( \frac{300km}{z_{up}} \right)^2 \tan^2 \theta f(x, z) K/s \]  

Here P is the power of the HF heater, V is the volume of the HF absorbed region, n_e is the electron density in this region, while \( \mu \) is the absorption efficiency. \((x, z)\) describes the spatial distribution of the HF beam power density taken as

\[ f(x, z) = e^{-(x-x_0)^2/a^2} e^{-\ln 2(z-z_{up})^2/b^2} \]  

118 The center of the heated region is taken at the upper hybrid altitude \( z_{up} \). Furthermore, \( b \) is the half-power beam width near the upper hybrid point. The HF-irradiated spot is taken as a circle centered at \( x_0 \), having the angular half-widths \( \theta \) so that \( b = z_{up} \tan \theta \), and the HF-irradiated volume is \( V = \pi ab^2 \). Finally, it is assumed that electron heating occurs in an altitude \( \Delta z \) range having the vertical extent \( a \) between the wave reflection point and the upper hybrid height, which is \( \Delta z \) dominated by the anomalous absorption [Gurevich et al., 1996].

128 [6] In this paper we will model the ionospheric conditions at Tromso during 10/07/99 at the time of the EISCAT experiment [Rietveld et al., 2003]. We therefore use in the SAM12 code the corresponding \( A_p \) and \( F_{10.7} \) indexes, and assume that the heating began 10/7/99 at 19:24 UT. The radiated HF power was 960 kW, the half power beam width \( 12^\circ \), and the facility was operated at a frequency of 4.5 MHz. Furthermore, for the unperturbed profile of the electron density we find that the reflection height for the 4.5 MHz frequency is located at 280 km, while the upper hybrid height is at about 10 km below. Thus the vertical extent of the anomalous absorption region is taken as \( a = 10 \) km.

141 [7] Before proceeding we should caution the reader on the timescale of model validity. The model neglects the horizontal transport caused by the Earth’s magnetic field, which has a time scale \( t_{dr} = b/v_{dr} \), where \( v_{dr} \) is the drift velocity and \( b \) is the horizontal scale of the heated region. Taking into account that the Tromso HF-heater has a half-power beam width of \( 12^\circ \) and that the electron heating occurs at an altitude of 300 km, we obtain that the horizontal scale of the heated region is \( b = 60 \) km. Moreover during the time of the disturbed experiments the detected drift velocity was 200-300 m/s [Rietveld et al., 2003]. Thus the Earth’s magnetic field leads to energy loss followed by the reduction of the heating effect on a time scale of 3.5–5.0 minutes.

2.1. Simulation Procedure

[8] The code starts up from empirically determined initial conditions 24 hours before the specific heating time, and runs for 24 hours of ‘world clock time’. This practice allows the system to relax to ambient conditions, and reduces noise in the system due to the initialization. Furthermore, the neutral density model was adjusted so that the computed \( f_0F_2 \) peak matched the observed. Then the “artificial heater” turns on and begins to pump energy into the electrons, using the specified parameters for that run. Artificial heating continues for some time continuously pumping energy into the electrons at the specified altitude, and the perturbations in ion and electron properties are tracked as they travel along the field line. Then the heater switches off, allowing the ionosphere to relax back to ambient conditions. The latter may also vary according to the natural factors which determine the ionosphere dynamics. This procedure minimizes noise due to the initialization and allows for the perturbations in the ionosphere to travel along the field lines, and the ionosphere to relax following strong heating. It describes the plasma response to the removal of the artificial heating as well as its application.

[9] In order to isolate and measure the perturbations directly, a duplicate set of runs was made, identical to the run described, but with a different heating rate defined by factor \( q \) in equation (1). In addition, one run without artificial heating was performed. We refer to this as “ambient” or “reference” run, while those with artificial heating are “heated” runs. The ionosphere changes during a simulation due to natural causes, so the perturbations in the heated runs due to artificial heating would not be easily identifiable on their own. But since the same natural variations are present in the ambient data, scaling (or subtracting) by the ambient data provides a simple way to decouple the natural variations from the heater induced perturbations.

3. Discussion

3.1. Comparison With Tromso Experiments

[10] In order to reproduce results of the ISR observations made at Tromso we conducted some runs using the specified conditions at Tromso 10/7/99. Namely, we considered the index \( A_p = 5 \) and that the HF heating began at 19:24 UT. For the specified heater and antenna characteristics at EISCAT equation (1) gives that \( q = 12,400 \), \( \mu \) K/s. In our runs the heating rate varied in the range 2,000–8,000 K/s which corresponds to the absorption efficiency \( \mu = 0.16–0.64 \). Note that Gustavsson et al. [2001] used the radar data collected during the heating experiments at Tromso to estimate the heating rate per electron as 3,000 K/s. This value corresponds to the absorption efficiency \( \mu = 0.25 \), which is within the range of our estimates.

[11] Figure 1 shows the height profile of the electron density normalized to its ambient value computed at different times for a given pumping rate \( q = 8,000 \) K/s which corresponds to an absorption efficiency \( \mu = 0.64 \). The heating was switched on at 19:24:00 UT for 8 minutes. The traces labeled 1 to 3 correspond to times separated by 3 minutes starting at 19:25:46, i.e. 1 min and 46 s into the heating. The trace 4 corresponds to cooling over 2 minutes and 49 seconds. Figure 1 reveals that the electron heating increases the plasma pressure and thus pushes the plasma from the heated region along the magnetic field line. Consequently, the plasma density in the heated region drops by more than 20%, but on a timescale larger than 5 minutes, as shown by the trace 3.

[12] Figure 2 shows the results of our model superimposed onto the observation results presented by Rietveld et al.
et al. [2003, Figure 3]. The latter were made by the EISCAT ISR at 19:28 UT. Figure 2 (left) shows the observed altitude profile of the electron density (circles) and that computed by the SAMI2 model (continuous trace) for 4 minutes in the heating. Figure 2 (middle) shows the observed ion temperature (circles) and electron temperature (crosses) along with the three traces generated by SAM12 model. In order to improve agreement between the model and observations the neutral density in the model was adjusted so that the computed $f_o F_2$ peak matches the observation.

Figure 1. The electron density normalized to its ambient value computed at different times for a pumping rate $q = 8,000 \, \text{K/s}$ which corresponds to the absorption efficiency $\mu = 0.64$. The heating was switched on at 19:24:00 UT for 8 minutes. The traces labeled 1 to 3 correspond to times separated by 3 minutes starting at 19:25:46, i.e. 1 min and 46 s into the heating. The trace 4 corresponds to cooling over 2 minutes and 49 seconds.

Figure 2. (left) The observed altitude profile of the electron density (circles) and the one computed by SAMI2 (continuous trace) for the four minute time interval starting on at 10/07/99 at 19:24:00 UT. (middle) The observed ion temperature (circles) and electron temperature (crosses) along with the three traces generated by the SAMI2 model. The dashed, solid, and dot-dashed line corresponds to the absorption efficiencies $\mu = 0.16, 0.32$ and 0.64 respectively. (right) The observed ion velocity (diamonds) along with the three traces which correspond to the computations made at $\mu = 0.16, 0.32$ and 0.64 (from left to right).
230 observations. For this purpose we have reduced the density of 231 the atomic oxygen in the model by 50%. Such an approach is 232 justified by the fact that SAMI2 uses averaged model values 233 of the neutral density which may not be very accurate. The 234 adjustment leads to significant changes in the electron 235 temperature and affects the vertical velocity only slightly. 236 The dashed, solid, and dot-dashed lines in Figure 2 corre- 237 spond to the absorption efficiencies \( \mu = 0.16, 0.32 \) and 238 0.64, respectively. Note that the changes in \( \mu \) affect only 239 the values of electron temperature, while the ion temper- 240 ature remains unperturbed during a relatively short heating 241 pulse. Figure 2 (right) shows the observation of the ion 242 velocity (diamonds) along with the three traces which 243 correspond to the computations made at different absorp- 244 tion efficiencies \( \mu = 0.16, 0.32 \) and 0.64 (from the left to 245 right). Also, in this case the HF heating duration did not 246 exceed the time scale of \( E \times B \) drift and thus the energy 247 loss due to horizontal transport can be neglected. 248 [14] Figure 2 reveals that (1) HF heating with the absorp- 249 tion efficiencies \( \mu = 0.3–0.6 \) drives perturbations of the 250 electron temperature in good agreement with those detected 251 by the ISR and (2) The computed ion velocity fits well with 252 the observations. Namely, it shows that the ion velocity is 253 close to the heating region, and positive above it. A 254 strong electron heating increases the electron pressure and 255 pushes the plasma both down and upward from the heated 256 region. Thus below this region the ion velocity is negative 257 (downward directed), while above the region it is positive 258 (upward directed) and its value increases with altitude 259 since the plasma propagates in the ionosphere of deca- 260 density. 261 3.2. Comparison With SURA Experiments 262 [15] Frolov et al. [2008] reported the detection of plasma 263 ducts by the DEMETER satellite overflying the SURA HF- 264 heater. In fact, ducts were detected when the heater operated 265 at 4.3 MHz, and at ERP = 80 MW, while the half-power 266 beam width was 12° on 05/01/06. The ionosphere was quiet, 267 \( Kp = 0 \), and the heating wave was reflected at 230 km, 268 below the \( f_0F_2 \) peak. 269 [16] We conducted SAMI2 runs for this day for SURA 270 location (56°N, 46°E) using the specified characteristics 271 of the HF-heater. The heating began 10 minutes before 272 273 the DEMETER overfly at 18:28:39 UT, and lasted for 274 15 minutes. Figure 3 shows the relative changes in the density of \( O^+ \) ions computed for the two different pumping 275 rates \( q = 1,000 \) and 1,700 Ks which correspond to the absorption efficiency \( \mu = 0.17 \) and 0.29 respectively. The increase in \( O^+ \) density was then checked against the DEMETER observations shown by crosses. The latter data 276 were derived from the DEMETER observations of the time 277 series of \( O^+ \) density [Frolov et al., 2008]. We converted 278 these data into the relative ion density by dividing them by 279 the value of the unperturbed \( O^+ \) density measured outside the 280 duct. In addition, we presented the relative \( O^+ \) density as a 281 function of latitude by taking into account the orbital velocity 282 \( v = 7 \) km/s of DEMETER. Figure 3 shows a good agreement 283 between the observations and model for the case of the absorption efficiency \( \mu = 0.17 \). Note that similar HF heating 284 experiments were conducted at HAARP using Demeter as a 285 diagnostic tool [Milikh et al., 2008]. 286 3.3. Concluding Remarks 287 [17] Recently modified SAMI2 numerical model was val- 288 idated by comparison with two well documented experi- 289 ments. One experiment, conducted at the SURA heating 290 facility, used the low orbit satellite DEMETER as a diag- 291 nostic tool to measure the electron and ion temperature and 292 density along the overflying satellite orbit close to the 293 magnetic zenith of the HF-heater. The second experiment, 294 conducted at the EISCAT HF facility and diagnosed by the 295 EISCAT ISR, measured the vertical profiles of the electron 296 and ion temperature between 150–600 km. The model 297 reproduces the observations with high accuracy, which 298 indicates its potential as a key tool for study of the arti- 299 ficial ducts, and to guide future observational campaigns. In 300 addition, the model predicts that the ionospheric HF heating 301 could produce strong perturbations of the plasma pressure 302 which will then transform into magnetic field perturbations 303 that could be detected by low orbit satellites having on-board 304 magnetometers such as DMSP. Moreover by checking the 305 model results against the ISR or satellite made observations 306 one can assess efficiency of the duct production, namely what 307 fraction of the radio beam energy was pumped into the ducts. 308 309 [18] Acknowledgments. The work was supported by DARPA via a 310 subcontract N684228 with BAE Systems. It was also supported by the 311 ONR grant N0017302C60 and by the ONR MURI grant 312 N000140710789. The work of A.D. was also supported in part by the Russian 313 Academy of Sciences (the Program "Plasma Processes in the Solar System"). 314 315 References 316 Berthelier, J. J., et al. (2006a), ICE, the electric field experiment on 317 DEMETER, Planet. Space Sci., 54, 456–471, doi:10.1016/j. 318 pss.2005.10.016. 319 Berthelier, J. J., et al. (2006b), IAP, the thermal plasma analyzer on 320 DEMETER, Planet. Space Sci., 54, 487–501, doi:10.1016/j. 321 pss.2005.10.018. 322 Carpenter, D. L., M. A. Spasojević, T. F. Bell, U. S. Inan, B. W. Reinisch, 323 J. A. 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