<u>Preliminary results of the SURA-DEMETER experiment carried out in 2005.</u>

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The goal of the SURA-DEMETER experiment is to study at the height of DEMETER orbit (h = 710 km) features of artificial ionosphere turbulence (AIT) produced due to the interaction of O-mode powerful radio waves, radiated by the Sura heating facility, with ionosphere F-region plasma. In the report it is discussed some results, related to AIT features, which were obtained during measurements carried out in 2005.

The measurements discussed here were conducted at the Sura heating facility of the Radio Physical Research Institute (NIRFI), Nizhny Novgorod, Russia (geographic coordinates, 56.13 N, 44.1°E, the magnetic dip at F region heights over the Sura facility is 71°). The Sura facility consists of three HF broadcast transmitters; each of them generates in the frequency range 4 – 25 MHz the maximum output power of 250 kW in the continuous mode of radiation. Each of three transmitters is connected to a subantenna array with dimensions 100 × 300 m^2 (elongated in the E−W direction), which consists of 4 rows of 12 wideband crossed dipoles operating in the frequency range 4.3 − 9.5 MHz. Such a three-module configuration of the facility allows radiating independently up to three pump waves of either left or right circular polarization with different frequencies, powers, and timing for each of them. When all three facility modules radiate coherently, the Sura facility has the effective radiated power (ERP) of 80 MW at 4.3 MHz, which increases up to 280 MW at 9.3 MHz with pump wave frequency growth. It corresponds to a pump intensity of ~ 0.5 − 1 mW/m^2 at 200 km altitude if both linear and nonlinear absorption of pump wave energy in the lower ionosphere is disregarded. The antenna beam can be steered in the geomagnetic meridian plane within a range of ± 40° off the vertical.

The Demeter satellite is the first in a new series of micro satellites developed by CNES, which has been successfully used also to study ionospheric disturbances related to human activity, among them ionosphere pumping by powerful HF radio waves launched in the ionosphere by ground based transmitters. When it was possible, the burst mode for satellite equipment operation was used in our experiments for detecting various plasma parameters. Satellite board equipment allowed to measure the following AIT characteristics:

1. Both electron and ion density and temperature perturbations over the Sura facility with scale lengths of about of 10 – 100 km, which are generated near pump wave reflection level due to development of numerous plasma instabilities and can spread along the magnetic field lines in the external ionosphere up to the satellite heght.
2. Plasma noises at a plasma frequency of background plasma, which are enhanced by electrons HF-accelerated in the ionosphere disturbed volume.
3. ELF and VLF electromagnetic waves, which are generated in the ionosphere disturbed volume due to different plasma processes.

In Table 1 it is presented the schedule of the SURA-DEMETER experiment carried out in April – September 2005. In each heating séance the Sura facility operated in the CW mode for 15 – 20 min starting 10 min before the time of the closest point of the satellite trajectory to the center of HF-disturbed magnetic tube, which is marked in the third column of the table as the “closest distance". It was successfully carried out 11 heating séances, dates of which are presented in the second column of the table. In 8 séances the satellite was over the Sura facility and in 3 séances, noted by (*) in the first column of the table, it was near the magnetic conjugation point relatively to the facility location. In the fourth column it is sited the time when the burst mode was switch-on for satellite equipment operation. Information on PW frequency, effective radiated power, and the inclination angle of the pump beam from the vertical to the geomagnetic south is presented in fifth column.

Table 1

№	Date	Time (UT) when the satellite was in the closest point to the target and the value of the closest distance (Δx)	Time (UT) when the burst mode for data sampling was turn-on	PW frequency (f_0), effective radiated power (P_{eff}), and the angle of the pump beam from the vertical (geographic zenith) to the geomagnetic south
1*	2005-04-01	18:30:00; 300 km	—	4300 kHz; 80 MW; 12°
2*	2005-04-10	18:23:00; 77km	—	4785 kHz, 120 MW; 12°
3	2005-04-23	18:19:30; 56 km	—	5105 kHz; 80 MW; 0°
4*	2005-04-26	18:23:30; 95 km	—	5105 kHz, 100 MW; 0°
5	2005-04-30	18:25:30; 30 km	18:25:30 – 18:27:30	4600 kHz; 100 MW; 12°
6	2005-05-24	08:02:00; 65 km	08:00:30 – 08:03:00	5828 kHz; 150 MW; 0°
7	2005-05-25	18:20:00; 85 km	18:19:30 – 18:22	5828 kHz; 150 MW; 0°
8	2005-08-13	18:21:00; 60 km	18:20 – 18:23	4300 kHz; 40 MW; 0°
9	2005-08-22	18:14:00; 180 km	18:14 – 18:16	4300 kHz; 40 MW; 12°
10	2005-08-27	18:32:00; ~100 km	—	4544 kHz; 100 MW; 12°
11	2005-09-05	18:27:00; 45 km	18:26 – 18:28	4300 kHz; 80 MW; 0°

Experimental results.

First of all, it should be noted that measurements with CW pumping, carried out either under daytime conditions (séance №6) or when the satellite was over the conjugate point relative to the Sura location (séances №№ 1, 2, and 4), did not show any sensible variations of the turbulence parameters studied. When ionosphere modifications were carried out during evening hours (T = 22:00 – 22:40 LT) and in doing so a pump wave frequency was only slightly below of the F_2-region critical frequency (f_{0F2}), existence of HF-induced plasma turbulence in satellite background plasma as a rule was well observed. It should be mentioned that the fulfillment of both these conditions is a necessary to maintain AIT spreading into the external ionosphere and magnetosphere.

Below we consider some results of the SURA-DEMETER experiment being mainly focused on the most successful heating séances № 5 (on April 30) and №11 (on September 5) for which the satellite passed very close to the center of a HF-disturbed magnetic tube. These measurements were carried out under rather magnetically quite conditions when a magnitude of the Kp index was ~ 3 – 4 or ~ 2 – 3 on April 30 and September 5, respectively. It is important also that these heating séances were accompanied by operation of the satellite equipment in the burst mode. The latter give us additional considerable opportunities for the analysis of obtained experimental data.

I. HF-induced variations of plasma parameters.

In Fig. 1a and 2a it is presented the time behavior of some plasma parameters, related to measurements carried out respectively on April 30 and September 5, which are available through the DEMETER "Quick Look" website. In these figures can be clearly seen appearance of noticeable artificial variations of ion temperature and velocity when the satellite passed through the HF-disturbed magnetic tube; characteristics of these variations are well distinct from natural variations observed. In Fig. 1b and 2b it is shown variations of plasma characteristics obtained by means of the satellite equipment operated in the burst mode. Here at five upper panels it is presented the time behavior of such plasma parameters as electron and ion temperatures (T_e and T_i) and densities (N_e and N_i), as well as the velocity of ions (V_i); at the low panel it is shown the distance between the satellite and the center of HF disturbed magnetic tube. In the figures it is clearly seen switch-on of the burst mode for satellite equipment operation as sudden changes in strength of registered signals, which is determined by the discontinuity of registration time due to some peculiarities of equipment operation schedule. When the satellite passed through the HF disturbed magnetic tube it can be seen existence of a region with HF-induced variations of these plasma parameters well pronounced on the background of natural plasma variations. According these and others data obtained, variations of these parameters were registered in a region of about of ± 400 km around the closest point of a satellite trajectory to the center of HF-disturbed magnetic tube. It is apparent that the dimension of this region along satellite trajectories in the north-south direction is much larger than the dimension of the center part of the ionosphere disturbed volume near a PW reflection level (of about of 100 – 150 km), which is determined for the most part by the main lobe of the Sura antenna beam and in which strong plasma turbulence is excited.

In Table 2 values of variations of the plasma parameters detected by the *CETP* analyzer are presented for April 30 (the séance parameters taken from Table 1 are: $\Delta x = 30$ km, $f_0 = 4600$ kHz, $P_{eff} = 100$ MW, $\Delta\theta = 12°$) and September 5 (the séance parameters are: $\Delta x = 45$ km, $f_0 = 4300$ kHz, $P_{eff} = 80$ MW, $\Delta\theta = 0°$). It should be mentioned that the relative variations of the studied plasma parameters have been estimated as $2\cdot\langle(A_{max} - A_{min})\rangle\cdot\langle(A_{max} + A_{min})\rangle^{-1}$.

Table 2

	$\Delta T_e/\langle T_e\rangle$	$\Delta N_e/\langle N_e\rangle$	$\Delta T_i/\langle T_i\rangle$	$\Delta N_i/\langle N_i\rangle$	$\Delta l(N_e,T_e)$	$\Delta V_i/\langle V_i\rangle$	$\Delta l(V_i)$
April 30	10–15%	10–15%	4–6%	10–15%	~ 35 km	30–45%	~ 45 km
September 5	7–10%	8–16%	3–6%	15–20%	~ 25 km	10–20%	~ 50 km

Basing on the data presented in Table 2, we can conclude that:

1. On the average the relative fluctuations for T_e, N_e, and N_i have close magnitudes of about of 10 – 15 %; at that the relative fluctuations for T_i is 2 – 3 times weaker.
2. The magnitudes of relative fluctuations for T_e, N_e, T_i, and N_i are very nearly the same for the both days of observations. Some distinction is only observed for the relative fluctuations of the ion velocity, V_i, with its two times larger value on April 30, when plasma modification was carried out with higher efficiency (higher effective radiated power and the use of 12° antenna beam inclination to the south whereby stronger generation of artificial ionosphere turbulence is observed).
3. The special scales for electron temperature and density variations have close magnitudes of about of 25 – 35 km; a larger scale of about of 45 – 50 km has been detected for the variations of the ion velocity.

These results can be compared with data of satellite tomography measurements carried out at the Sura facility in August 2002 [Tereshchenko E.D., Khudukon B.Z., Gurevich A.V., Zybin K.P., Frolov V.L., Myasnikov E.N., Muravieva N.V., Carlson H.C. Radio tomography and scintillation studies of ionospheric electron density modification caused by a powerful HF-wave and magnetic zenith effect at mid-latitudes. // Physics Letters A, 325 (2004). Pp.381-388]. An example of the reconstruction of N_e variations in HF-disturbed ionosphere F region is demonstrated in Fig. 3. In these measurements it has been stated that:

1. Under night conditions HF heating considerably affects the ionosphere resulting noticeable changes in the electron density distribution practically throughout the ionosphere body up to heights of about of 600 km, which are much higher than the F layer peak altitudes.
2. Artificial large-scale plasma density irregularities occupy a large region in a horizontal direction, which is of about of 300 km being much wider than the ionosphere area illuminated by the main lobe of the heating antenna marked in Fig. 3 by dashed lines.
3. In the night-time ionosphere under quiet magnetic conditions the generation of quasi-periodical variations in the electron density with characteristic scales of 20 – 30 km along the satellite trajectory (in noth-south direction) was revealed in a much wider region than the ionosphere illuminated area.
4. When the antenna beam was tilted by 12° to the south, the strongest depletions with a negative plasma density variation $\Delta N_e/N_{e0} \approx 20\%$ was observed inside the illuminated area which is related to the magnetic zenith effect [Gurevich A.V., K.P. Zybin, and H.C. Carlson. The magnetic zenith effect. // *Radiophys. and Quant. Electron.*, (2005). *48(9)*, pp.772-787. (Engl. Transl.)].

It can be seen that as a whole there is a good agreement for variations of the electron density and their special scales in N-S direction observed in both the SURA-DEMETER experiment and tomography measurements.

In the light of the results obtained in the SURA-DEMETER experiment it should be mentioned also data obtained at the Tromsø facility during heating experiments carried out in nightside auroral ionosphere by Blagoveshchenskaya et al. [Phenomena in the ionosphere-magnitosphere system induced by injection of powerful HF radio waves into nightside auroral ionosphere. // Annales Geophysicae (2005). *23*, pp.87-100] and by Rietveld et al. [Ionospheric electron heating, optical emissions, and striations induced by powerful HF radio waves at high latitudes: Aspect angle dependence. // JGR (2003). *108(A4)*, 1141, doi:10.1029/2002JA009543]. In these experiments it is observed strong HF-induced T_e and T_i enhancements in a wide altitude range up to 600 km, as well as generation of HF-induced intense upward ion flows along the magnetic field lines. It would be interesting to compare in future results obtained in these experiments with the SURA-DEMETER data.

II. Spectral characteristics of HF-induced plasma oscillations.

The analysis of HF spectral data has not shown any HF-produced variations in plasma noises as it was observed, for example, by Vas'kov V.V. et al. [Geomagn. and Aeronom., 1995. *35(1)*, pp.154-158 (in Russian)]. It is most likely that the intensity of HF-induced plasma noise, which is enhanced by electrons accelerated in the ionosphere disturbed volume, was below of an *ICE* analyzer sensitivity level.

The analysis of VLF and ELF spectral data has shown that during heating séances multiform spectral structures are often observed in a frequency range from 0 to 1200 Hz and in a frequency range of about of 10 – 15 kHz, but, as a rule, it is difficult to separate them from natural events because we have not yet any clear criteria for such a separation. By way of an example in Fig. 4a ELF spectrum of received signal is presented; its electric field strength for different field components is shown in Fig. 4b. These data were obtained on April 30. It can be clearly seen that, when satellite was at a distance of ≤ 70 – 100 km from the center of a disturbed magnetic tube, strong electric field variations (~ 5mV) are observed in a frequency range up to ~ 500 Hz; the intensity of these variations is decreased with growth of its frequency. It should be mentioned that similar electric field variations were observed by Vas'kov et al. [J. Atm. Sol.-Terr. Phys. (1998). *60*, pp.1261-1274]. Unfortunately, a limited number of experimental data, obtained in 2005 in the framework of the SURA-DEMETER experiment, as well as the weak repetition of events registered, cannot allow us to perform reasonable classification of the phenomena observed. Here more detail processing of obtained experimental data and new experiments are needed.

In March-May 2006 new measurements in the framework of the SURA-DEMETER experiment were conducted, in which ionosphere modifications were carried out by means of a pulse mode for pump wave radiation, multifrequency pumping, and steering of the facility antenna beam in the geomagnetic meridian plane. At present data obtained here are in process. We plan to continue such measurements in future.

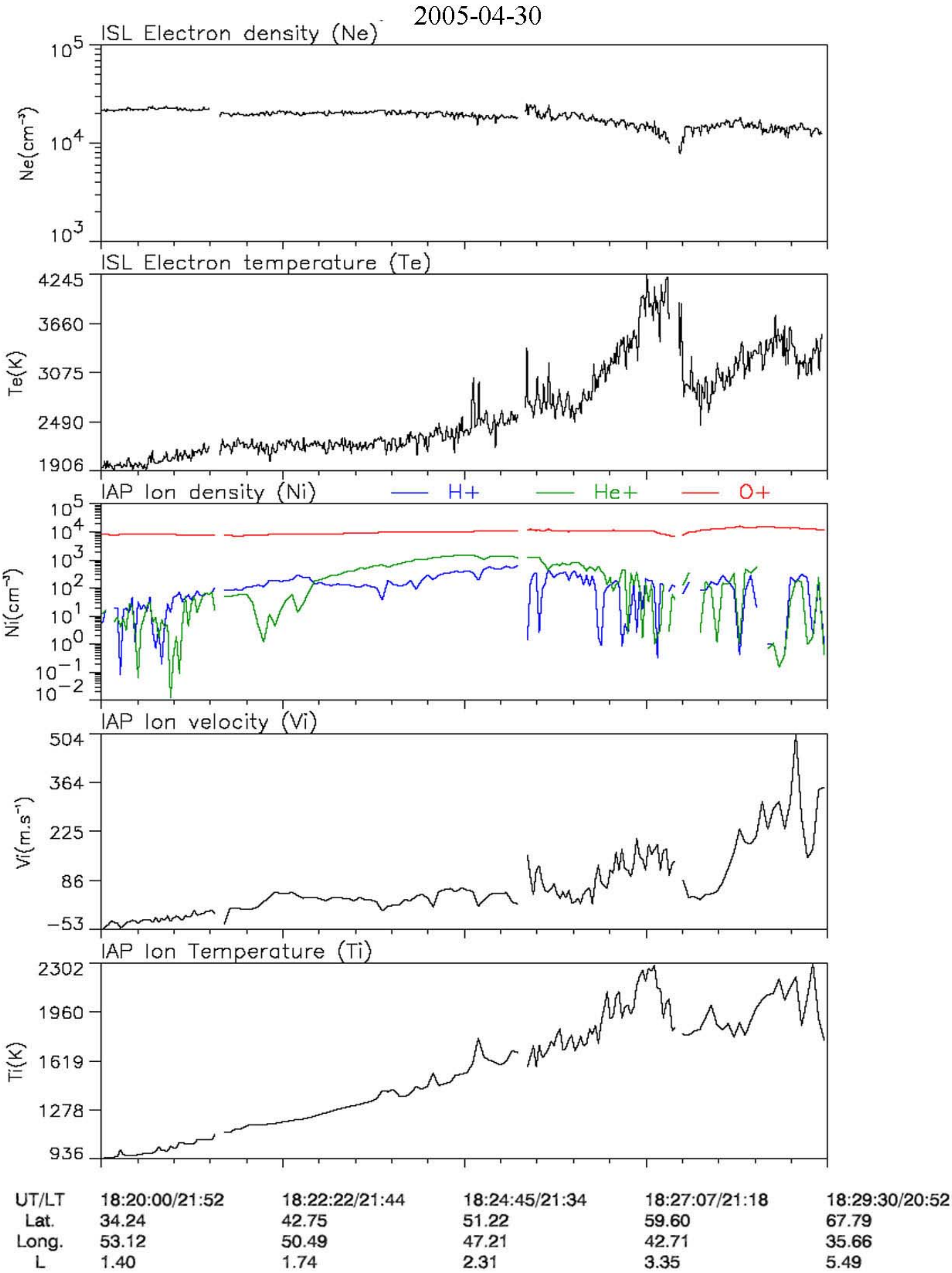

2005-04-30
ISL Electron density (Ne)
Ne(cm⁻³)
ISL Electron temperature (Te)
Te(K)
4245
3660
3075
2490
1906
IAP Ion density (Ni)
H+
He+
O+
Ni(cm⁻³)
IAP Ion velocity (Vi)
Vi(m.s⁻¹)
504
364
225
86
-53
IAP Ion Temperature (Ti)
Ti(K)
2302
1960
1619
1278
936
UT/LT 18:20:00/21:52 18:22:22/21:44 18:24:45/21:34 18:27:07/21:18 18:29:30/20:52
Lat. 34.24 42.75 51.22 59.60 67.79
Long. 53.12 50.49 47.21 42.71 35.66
L 1.40 1.74 2.31 3.35 5.49

Fig 1a

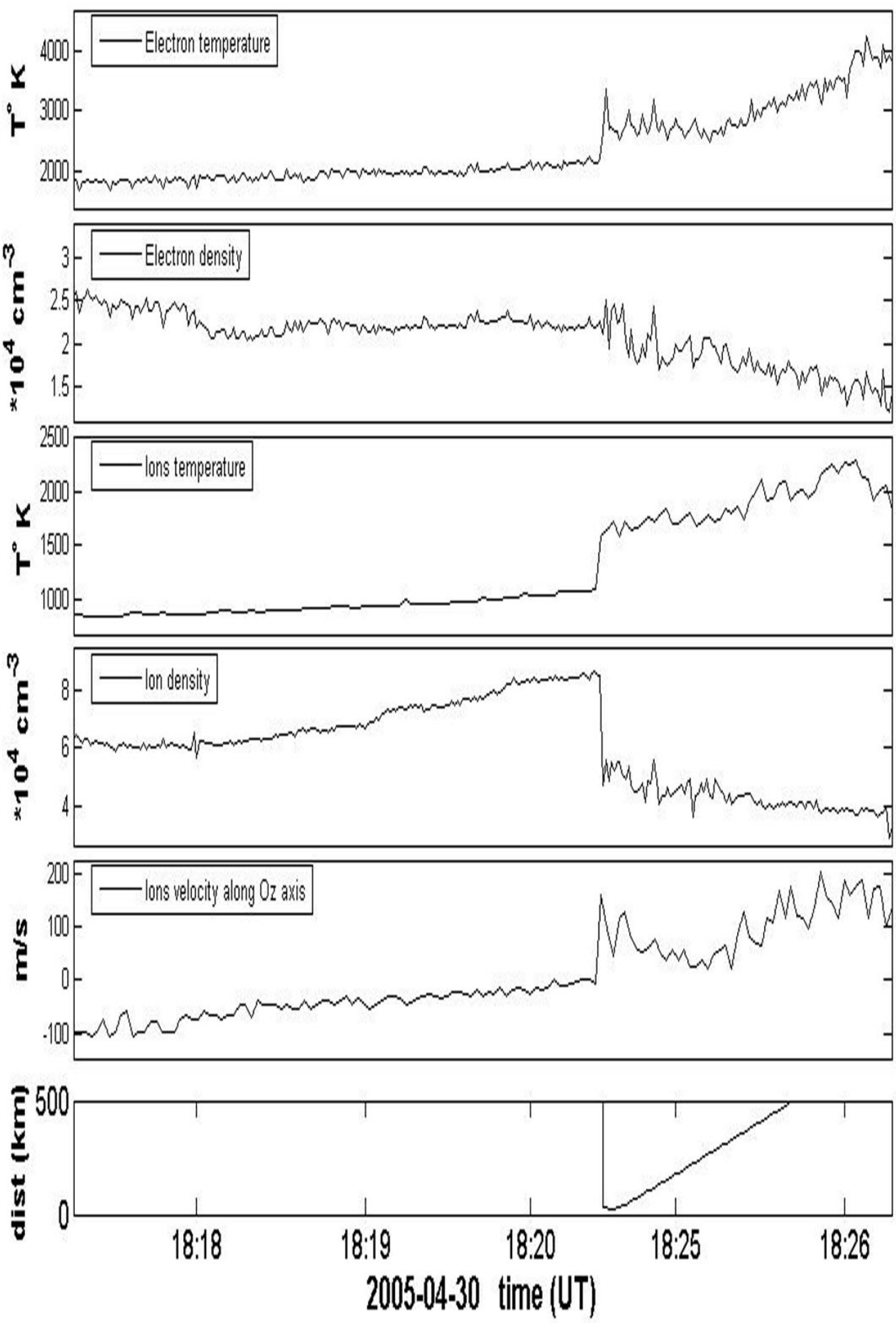

Electron temperature
T° K
4000
3000
2000
Electron density
*10⁴ cm⁻³
3
2.5
2
1.5
Ions temperature
T° K
2500
2000
1500
1000
Ion density
*10⁴ cm⁻³
8
6
4
Ions velocity along Oz axis
m/s
200
100
0
-100
dist (km)
500
0
18:18
18:19
18:20
18:25
18:26
2005-04-30 time (UT)

Fig 1b

2005-09-05

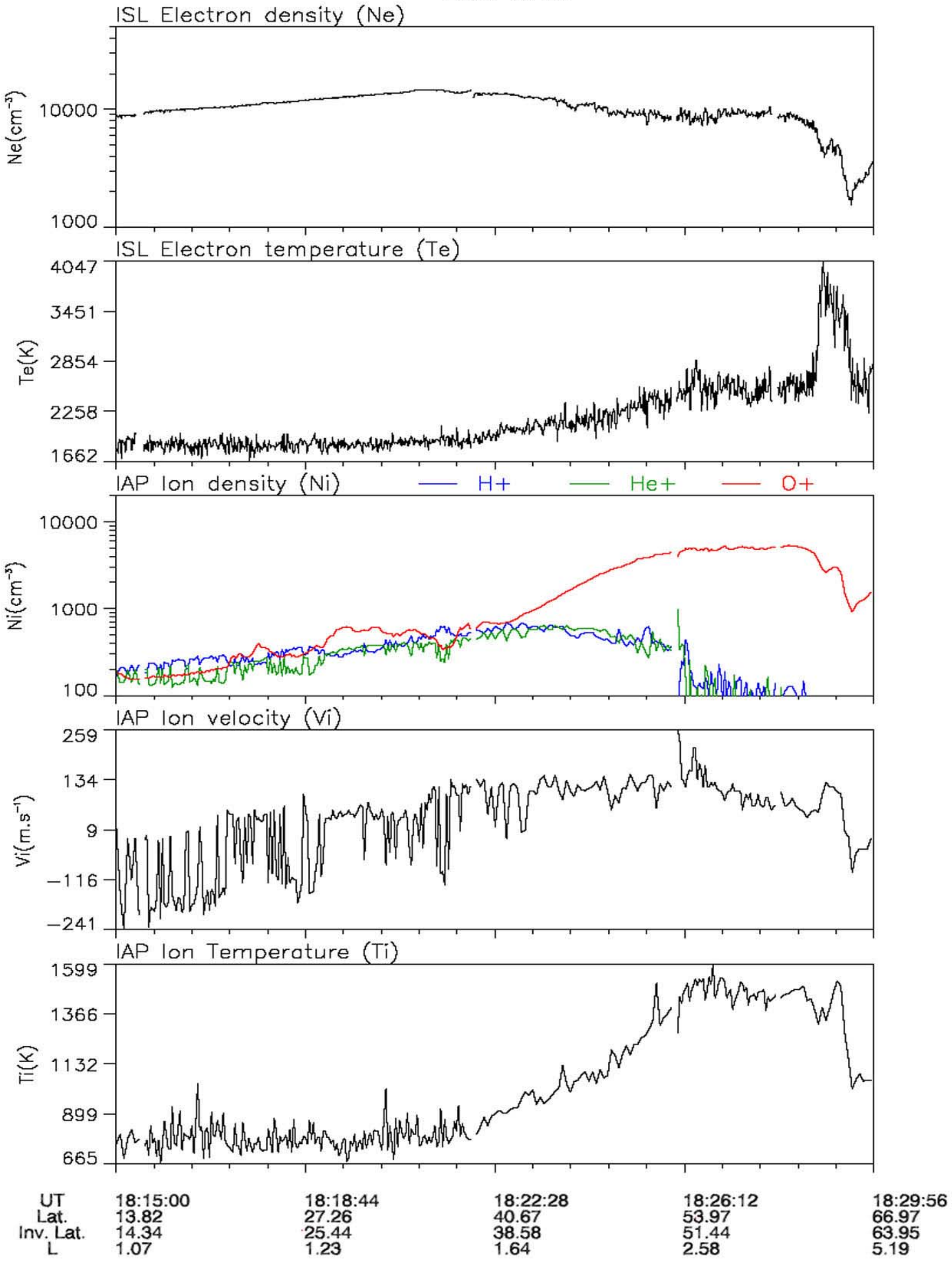
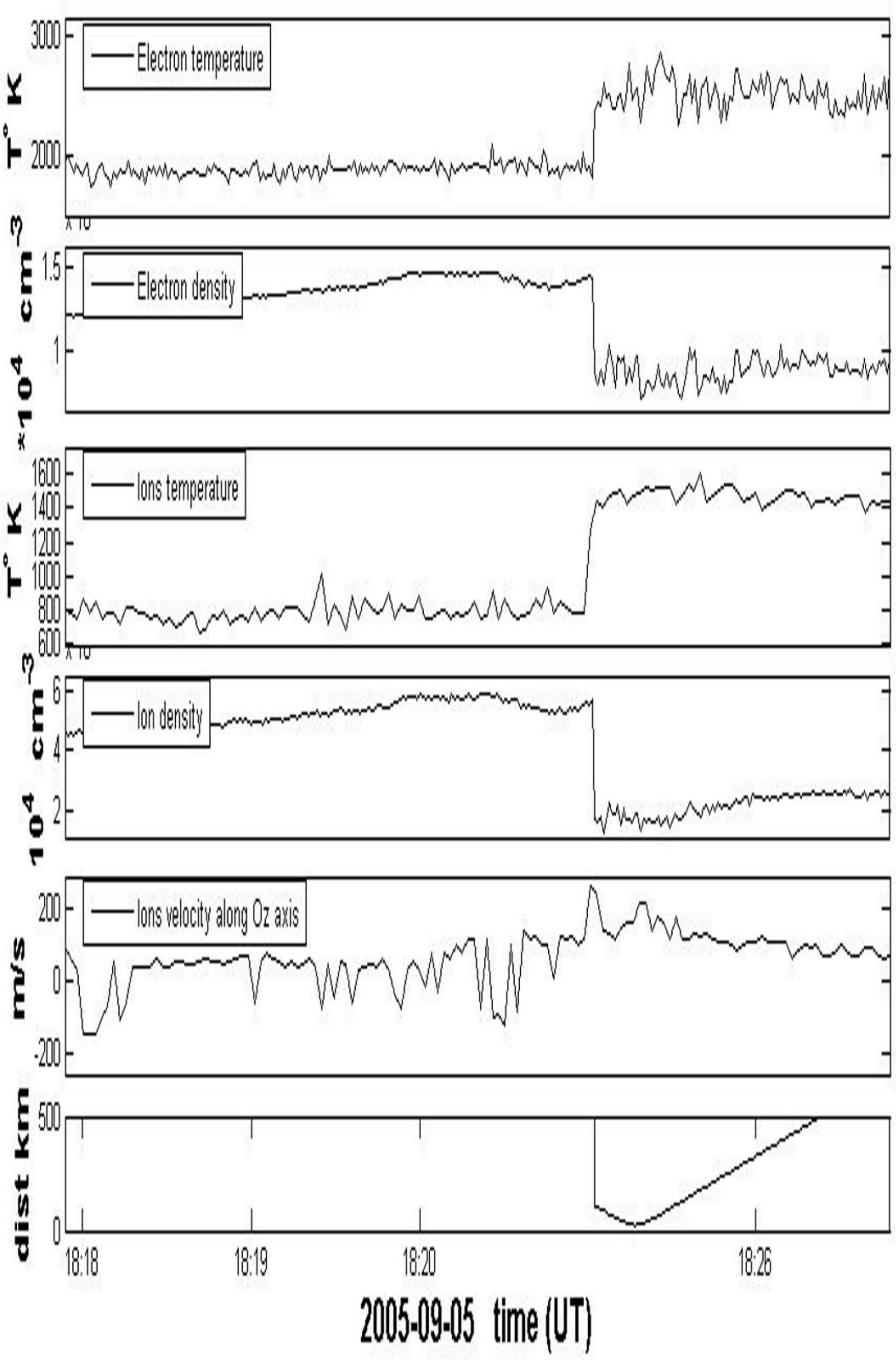


Fig 2a



Electron temperature
Electron density
Ions temperature
Ion density
Ions velocity along Oz axis
T° K
*10^4 cm^-3
T° K
10^4 cm^-3
m/s
dist km
18:18
18:19
18:20
18:26
2005-09-05 time (UT)

Fig 2b

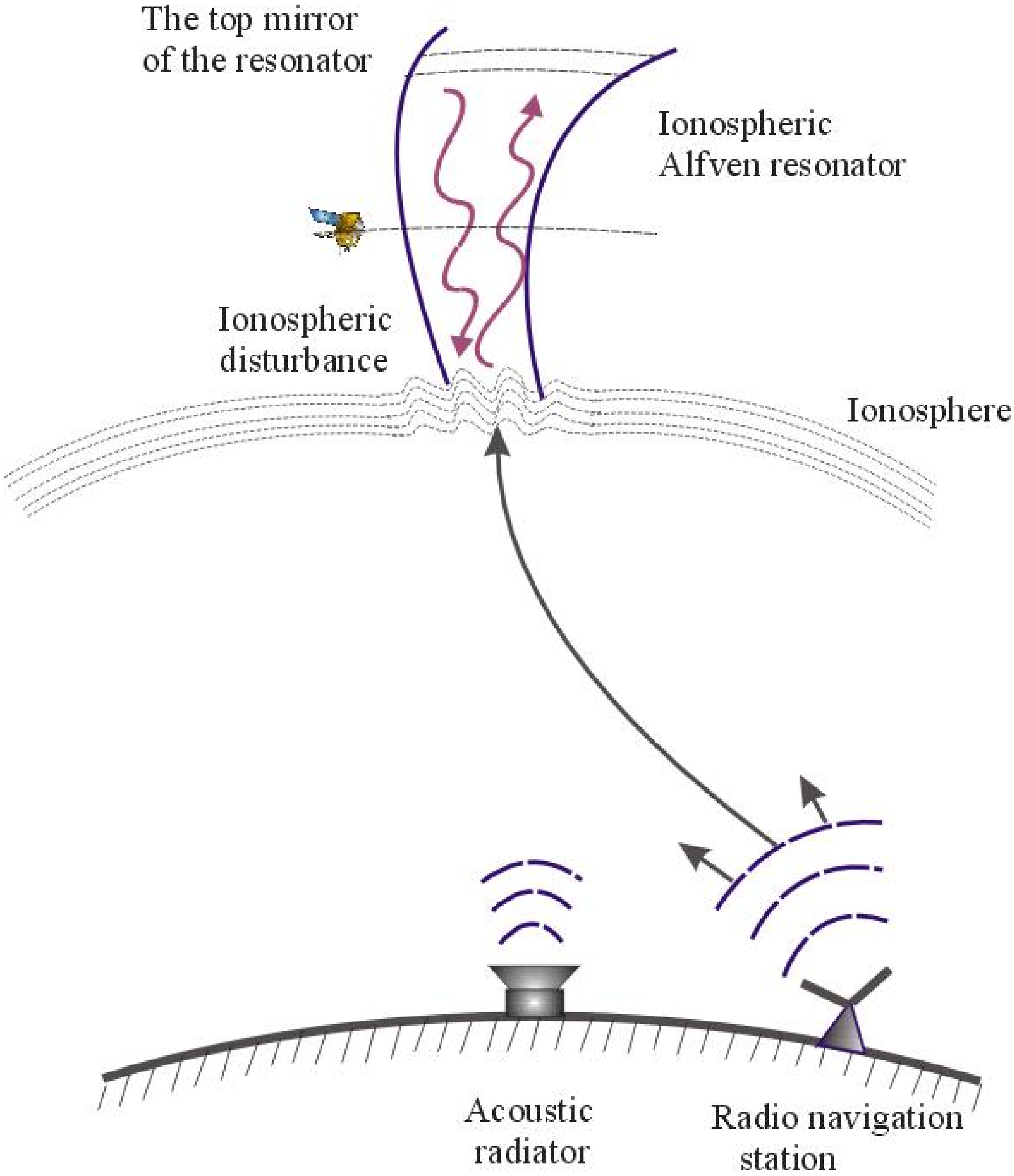
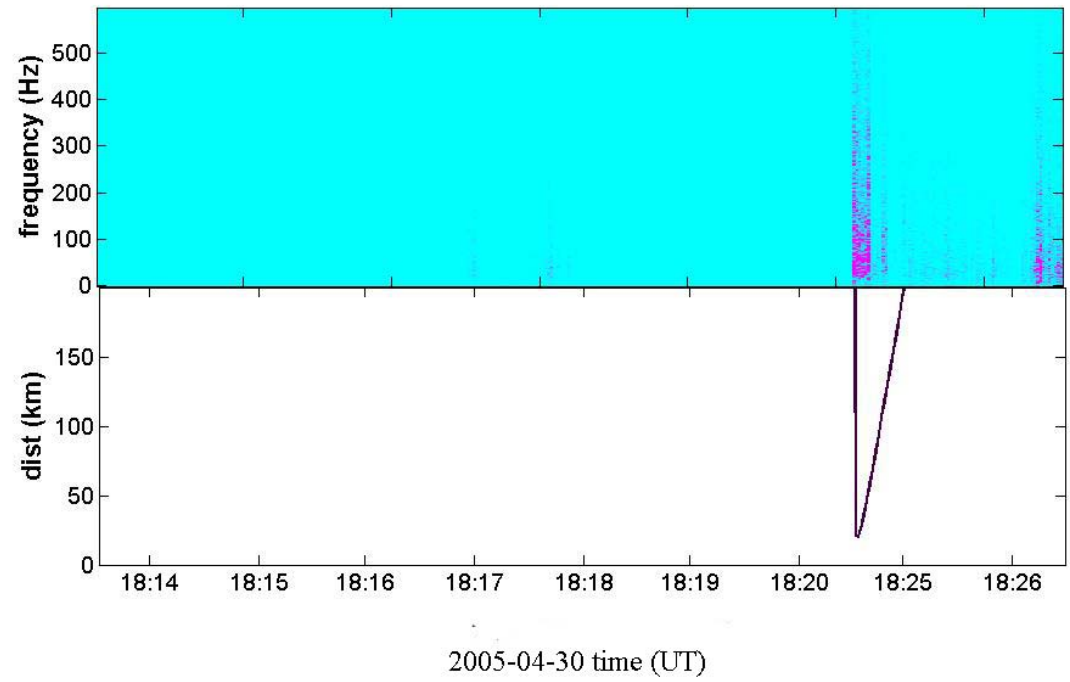
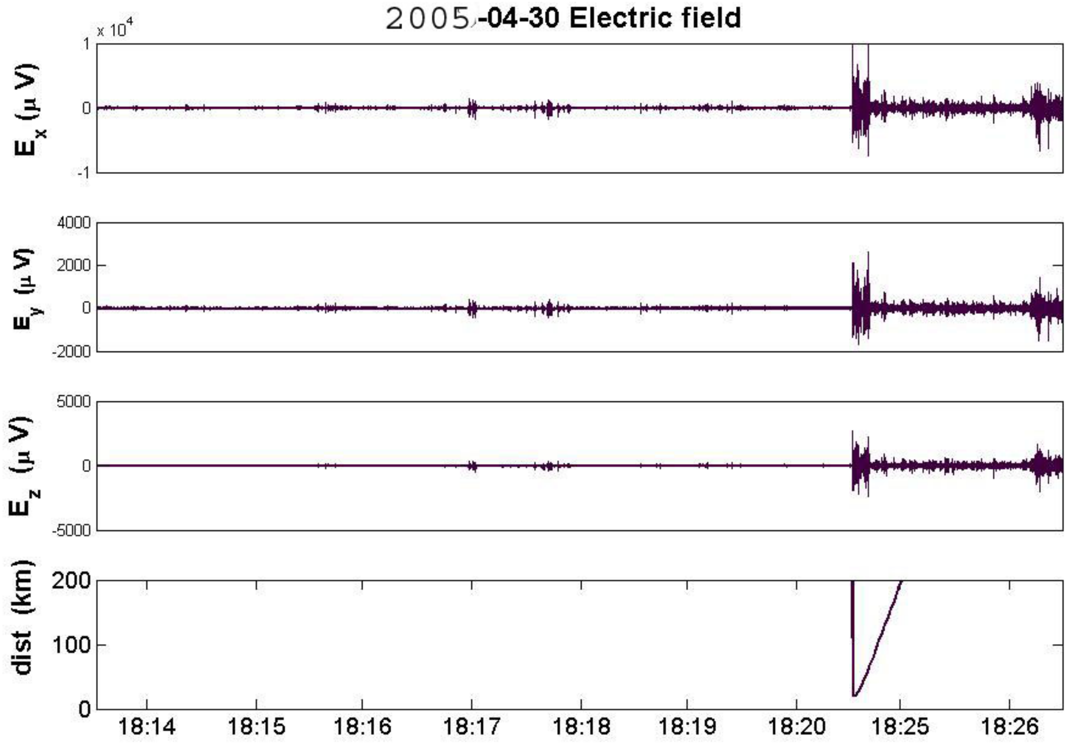


Figure 3. Model of ground-based acoustic excitation action on ionosphere


frequency (Hz)
500
400
300
200
100
0
dist (km)
150
100
50
0
18:14
18:15
18:16
18:17
18:18
18:19
18:20
18:25
18:26
2005-04-30 time (UT)


2005-04-30 Electric field
x 10^4
1
0
-1
E_x (μ V)
4000
2000
0
-2000
E_y (μ V)
5000
0
-5000
E_z (μ V)
200
100
0
dist (km)
18:14
18:15
18:16
18:17
18:18
18:19
18:20
18:25
18:26