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Doppler vertical sounding of the ionosphere at the Akademik Vernadsky station

Abstract. The paper aims at providing the technical information about Doppler vertical sounding of the ionosphere that started at the Ukrainian Antarctic Akademik Vernadsky station since 2017; developing the technique for processing and visualization of data of vertical sounding of the ionosphere in the form of height-time diagrams of median values of ionospheric parameters; demonstrating the capabilities of this technique using the results obtained during the first year of observations, namely the background variations of ionospheric parameters as well as examples of observations of travelling ionospheric disturbances (TID). The methods used in the paper are the following: the vertical sounding of the ionosphere using the IPS-42 ionosonde operating at Akademik Vernadsky station since 1982; Doppler vertical sounding of the ionosphere by the portable ionosonde developed and manufactured in collaboration between the Abdus Salam International Centre for Theoretical Physics (ICTP) and Institute of Radio Astronomy of the National Academy of Sciences of Ukraine (IRA NASU); calculating the height-time diagrams of ionospheric parameters obtained using the data of both ionosondes; and original technique for estimating the median height-time diagrams as background monthly averaged characteristics of the ionosphere. Seasonal and diurnal variations of plasma frequencies, vertical plasma velocities, as well as the signal-to-noise ratio and the probability of the registration of signals are shown using the median height-time diagrams of the corresponding parameters for the first year of synchronous observations by the two ionosondes. The features and potential areas of application of median ionospheric height-time diagrams are discussed. They can be used to calculate automatically variations of maximum usable frequency for a radio link of the specified length. Examples of TID registrations in variations of virtual heights of reflection and Doppler frequency shifts (DFS) of the signals are presented. It is shown that the comparison of TID manifestations in variations of virtual heights and DFS can be used to select a more appropriate model of TID among the models of perfectly reflecting moving surface or three-dimensional plasma density waves traveling through a real ionospheric layer. It could be concluded that simultaneous operation of two ionosondes at the Akademik Vernadsky station has allowed to significantly expand the amount and quality of objective information about the ionospheric behavior over the Antarctic Peninsula.

Keywords: ionosphere, Doppler sounding, ionogram, median value, height-time diagram, travelling ionospheric disturbances

1 Introduction

Ionosphere is a partially ionized layer of the Earth's atmosphere, where the level of ionization is enough to substantially affect the propagation of radio waves. Despite the fact that the ionosphere has been studied for about a hundred years, our knowledge does not yet allow obtaining a reliable forecast of ionospheric conditions even for a relatively short time (e.g., one day). Therefore, the investigation of ionospheric processes and the new methods development for their visualization, analysis and forecast remain highly relevant. One of the most widespread methods for ionospheric monitoring is a technique of vertical sounding of the ionosphere (VSI). Ionograms of ground-based vertical sounders are used to restore the vertical profile of electron density below its main maximum. To describe monthly averaged characteristics of the ionosphere median values of its parameters have been widely used since the middle of previous century (see, e.g., Beynon et al., 1961).

For visualization of various processes in the Earth's atmosphere, the height-time (HT) plot of different parameters is obtained using the incoherent scatter radars (Mitchell et al., 1998), meteorological radars (Bezvesilniy et al., 2003), lidars (Diettrich et al., 2005). The same technique also is used for visualization of VSI data (Haldoupis et al., 2006; Negrea et al., 2016). The height-time-frequency plots have been described and applied for studying the behavior of intermediate layers by Lee et al. (2003). It should be noted, the HT-diagrams of the intensity of the reflected signal were averaged over several days to study the variability of E_s in middle latitudes by Haldoupis et al. (2006).

The Antarctic Peninsula (AP) region is appropriate area for experimental studies of the troposphere-ionosphere energy transfer. This region is characterized by the quiet mid-latitude ionospheric background and is affected by the extremely high cyclonic activity, magnetic anomaly, and rapid variations in the total ozone content. Analysis of long-term data sets obtained at the Ukrainian Antarctic Akademik Vernadsky station (Akademik Vernadsky station) (former UK Faraday base) has allowed detecting the weather impact on the dynamics of middle and upper atmosphere above AP (Zalizovski, 2011). It has been possible due to long-term continuous meteorological, total ozone, geomagnetic and ionospheric observation, which has been carried out at Faraday/Akademik Vernadsky station for more than 60 years.

The atmospheric gravity waves (AGW) are the most effective transport agents for the energy transfer from low atmospheric layers to the ionosphere. AGW are propagating in the ionosphere as travelling ionospheric disturbances (TID). TID over the AP region were experimentally studied using the technique of frequency and angular sounding of the ionosphere (Beley et al., 1995; Galushko et al., 2008) in the framework of experiments carried out between the Arctowski station and the Akademik Vernadsky station in 2004 (Galushko et al., 2007), and the experiment conducted during 2015–2019 between Palmer station and the Akademik Vernadsky station (Paznukhov et al., 2017).

Measurements of ionospheric parameters are provided using the VSI techniques at the Akademik Vernadsky station since late 1950-s. A main device for ionospheric sounding is ionosonde IPS-42. The new portable Doppler ionosonde was installed at the Akademik Vernadsky station in 2017 as a supporting instrument. The Doppler ionosonde allows analyzing the vertical profiles of both the regular and short-term variations of vertical plasma velocity which is associated with TID.

The paper aims to provide the technical information on Doppler vertical sounding of the ionosphere that was started at the Akademik Vernadsky station in 2017. We describe the technique for processing and visualization of data of ionosphere vertical sounding in the form of height-time charts of median ionospheric parameters. The technique provides the background variations of ionospheric parameters as well as examples of observations of the TIDs.

2 Methods and data

2.1 Vertical sounding of the ionosphere

The main instrument for ionospheric sounding is ionosonde IPS-42 that has been used at Faraday/Akademik Vernadsky station since 1983. In April 2017, the new portable Doppler ionosonde (Zalizovski et al., 2018) was developed and manufactured in cooperation of Institute of Radio Astronomy of National Academy of Sciences of Ukraine (IRA NASU) and International Centre for Theoretical Physics (ICTP). This ionosonde has been installed at the Akademik Vernadsky station to support existing ionospheric observations. The main purpose of the newly developed instrument is to measure height-frequency characteristics of the ionosphere (also known as ionograms). An important advantage of the instrument is its ability to measure the Doppler frequency shift (DFS) of reflected signals on different carrier frequencies and to estimate the vertical projection of plasma velocity in a wide range of heights.

The construction principle of the new ionospheric sounder is based on the design of the DPS4 digisonde (Reinisch et al., 2007; Reinisch et al., 2018) with the new software (Software Defined Radio) for ionospheric sounding (Morris, 2014). The new ionosonde provides ionospheric diagnostics continuously.

The ionosonde has been operating with a sampling rate every 5 minutes since April 2017. This regime was selected to supplement the regular sounding by the conventional ionosonde IPS-42 that obtains one ionogram every 15 minutes. The experience obtained during long-term HF experiments with receiving site at the Akademik Vernadsky station (Zalizovski et al., 2007; Zalizovski et al., 2015) was used to design an operation schedule for two ionosondes. The new instrument performs the sounding using a grid of 22 carrier frequencies with the sounding duration being about 10 seconds for each frequency. This regime allows estimating the DFS with resolution of about 0.1 Hz. Hence the resolution of the estimated vertical plasma velocity in the HF band is in the range from 0.1 to 1 m/s. Besides the information about regular plasma velocities, the selected regime allows studying the wave-like processes in the ionosphere with periods from 10 minutes and more, for example medium- and large-scale travelling ionospheric disturbances (TID).

In order to optimize the analysis of the increased volume of VSI data, we have developed an approach that allows presenting the average characteristics of the ionosphere for the sufficiently long time period (about a month) in the form of median height-time diagrams. The technique for their calculation is described below.

2.2 A technique for calculating the height-time diagrams

Algorithm for constructing the HT-diagram of the median values of an ionospheric parameter is very similar to the algorithm for calculating the dynamic diagram. The only difference is that instead of dynamic non-averaged data, the monthly median value of the parameter for each height-time cell is calculated and plotted. Below we briefly describe the procedures required to construct a diagram.

The result of VSI is the height-frequency characteristic of the ionosphere, or ionogram, which is a 2-dimensional matrix containing information parameter values. For the ionosonde developed by IRA NASU both the level of reflected signal and DFS are measured and stored in the form of two matrices, for the IPS-42 ionosonde only the binary value representing the presence of the reflected signal can be obtained. Both ionosondes cannot detect the polarization of the received signals because they use linearly polarized antennas oriented in the same plane.

The first stage of processing is "cleaning" procedure that aims at excluding the noise from the ionograms. It is worth noting that the algorithm and parameters for "cleaning" procedure should be chosen individually for each instrument location based on the quality of its ionograms. The quality, in turn, is determined not only by the characteristics of the equipment but the noise conditions at the site of measurements.

At the next stage, the maximum reflected frequency for each virtual height is estimated. This value is considered to represent plasma frequency and depicted in color on the HT-diagram in the corresponding height-time cell. Because of the absence of the discrimination of O- and X-mode signals in both ionosondes, the frequency of X-mode is interpreted as the plasma frequency in most of the cases.

HT-diagrams of vertical velocity are constructed from the estimations of the Doppler frequency shift

F_D converted to virtual vertical plasma velocity using equation $V_r^{\prime} = \frac{1}{2}\frac{F_D c}{f}$ for the height-time cells when and where the reflected signal is present in this cell. In this equation f is the carrier frequency, c — the light speed. The new ionosonde provides the information about signal-to noise ratio for each cell. This information can be useful for analyzing the propagation conditions and distinguishing reflections from different ionospheric layers. HT-charts of signal-to-noise ratio are built similarly to the HT-diagrams of plasma frequencies and vertical velocities.

The final processing step is calculating and constructing the median HT-diagrams. For that the median value of the information parameters are calculated for each height-time cell. To obtain a reliable median value, only the cells with a certain minimum number of data points have been selected. As a rule, the minimum number was chosen to be greater or equal to five. Obtained HT-diagrams allow analyzing the background diurnal variations of the ionospheric parameters as a function of time and virtual height.

3 Results and discussion

3.1 Median HT-diagrams

The median monthly "virtual height-time" diagrams of plasma frequencies of the extra-ordinary wave, vertical plasma velocity, signal-to-noise ratio, and probability of the presence of the reflected signal at the Akademik Vernadsky station are shown in Fig. 1. The IPS-42 data were used to create HT-diagrams of plasma frequencies shown in the first column of Fig. 1. The HT-diagrams shown in the second, third and fourth columns are constructed using the data from the new Doppler ionosonde.

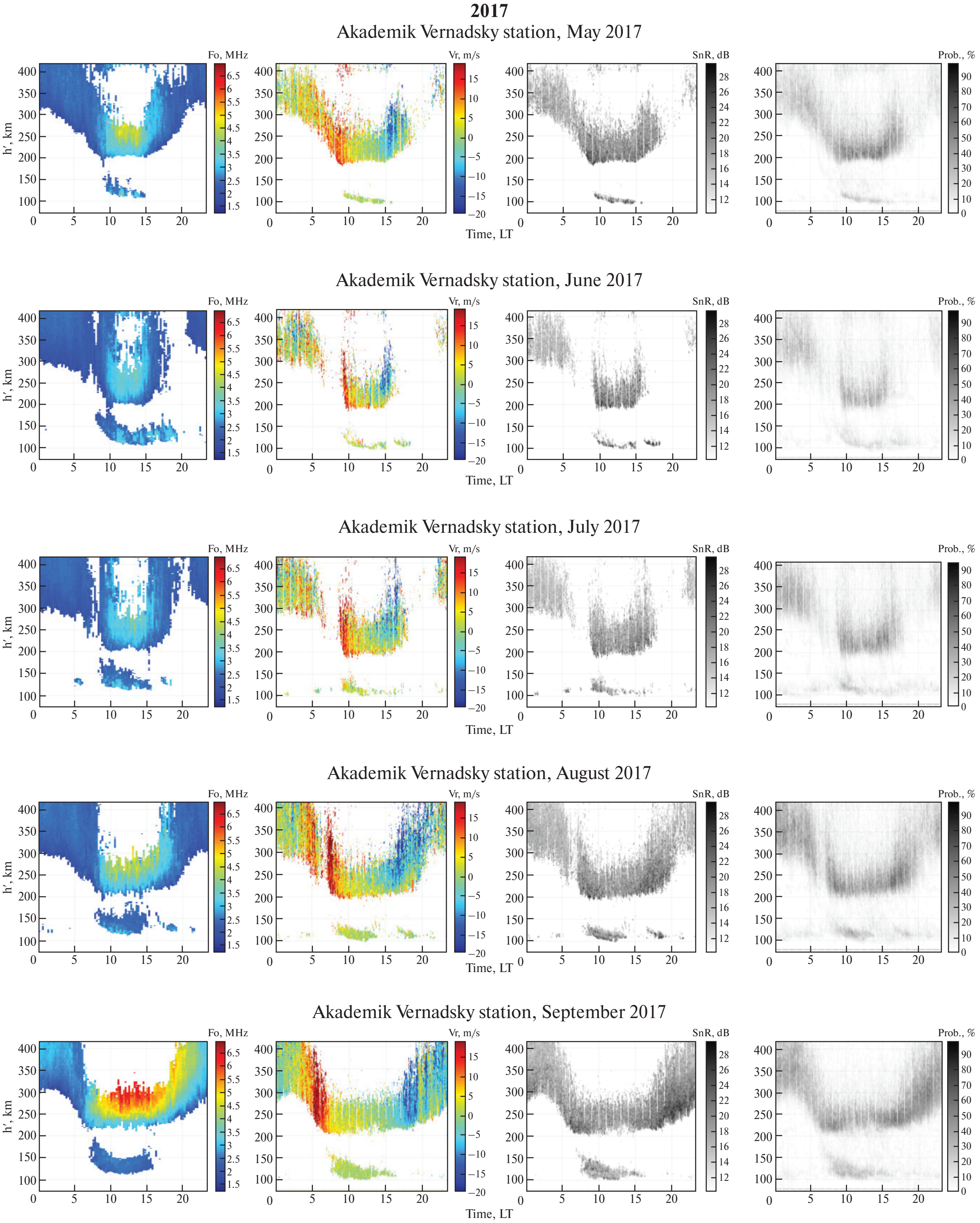
The big seasonal and diurnal variations of the ionospheric parameters are seen over the Antarctic Peninsula. From May till August the reflections from E region (90—150 km) are absent during the night time. The height of the lower boundary of F2 region rises above 300 km near midnight. During the daytime reflections from E region appear and the virtual height of the lower border of F region goes down to 200 km.

An asymmetry in the daily variation of the ionosphere parameters can be observed in the behavior of the plasma frequencies during equinoctial months (September, October, February, March, partially April). It manifests as the time shift of the higher values to the evening (see Fig. 1, column 1).

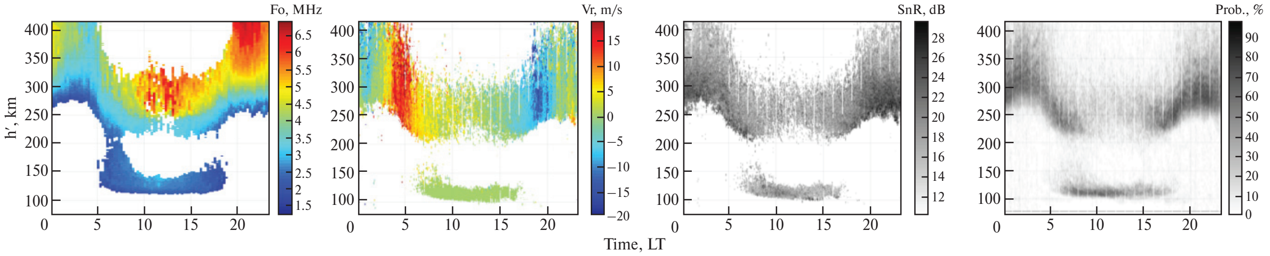
The culmination of this phenomenon is observed from November to January, when the maximum of ionization is shifted to the midnight, and minimum to the daytime. This effect was observed for the first time at Halley station (Bellchambers, Piggott, 1958), and since that time got the name of Weddell Sea anomaly (WSA). But the strongest inversion of the daily variation is observed at the Argentine Islands where the Akademik Vernadsky station is located. It should be noted that WSA is the most remarkable example of how the dynamics of neutral atmosphere can impact the upper ionosphere, in particular the electron peak density and total electron content. The correct explanation of WSA as a result of thermospheric wind impact was made for the first time by Kohl, King (1967). This behavior is associated with the presence of the equatorward component of the thermospheric wind at night, which transfers the plasma upward due to the ion drag mechanism. In the daytime, on the contrary, the increase in plasma concentration is depressed by the poleward component of the thermospheric wind leading to plasma downwelling.

It is interesting that the plasma vertical velocity measured by the new ionosonde for the midnight hours of November-January (Fig. 1, column 2) is close to zero. We suppose that it does not mean that the plasma does not move upward, but the plasma motion is a part of the dynamical equilibrium, which provides the stable F layer at this time. Due to stable parameters of F layer the phase path of signals reflected from it are constant, therefore signal's DFS remain near zero.

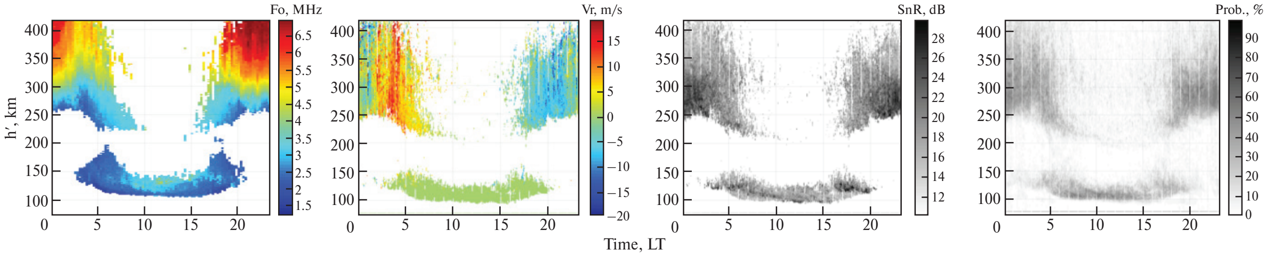
It can be noted that the regular dynamics of the F layer and the values of the plasma vertical velocity shown at second column of Fig. 1 are in a good agreement. When the F layer moves down in the morning the regular values of DFS are positive in all the height range. And vice versa, when the layer moves upward


2017
Akademik Vernadsky station, May 2017
Akademik Vernadsky station, June 2017
Akademik Vernadsky station, July 2017
Akademik Vernadsky station, August 2017
Akademik Vernadsky station, September 2017
h′, km
100
150
200
250
300
350
400
Time, LT
0
5
10
15
20
Fo, MHz
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
Vr, m/s
−20
−15
−10
−5
0
5
10
15
SnR, dB
12
14
16
18
20
22
24
26
28
Prob., %
0
10
20
30
40
50
60
70
80
90

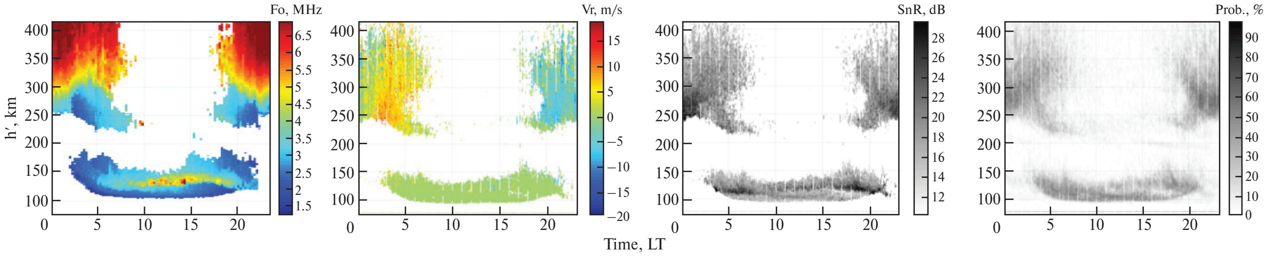
Akademik Vernadsky station, October 2017



Akademik Vernadsky station, November 2017

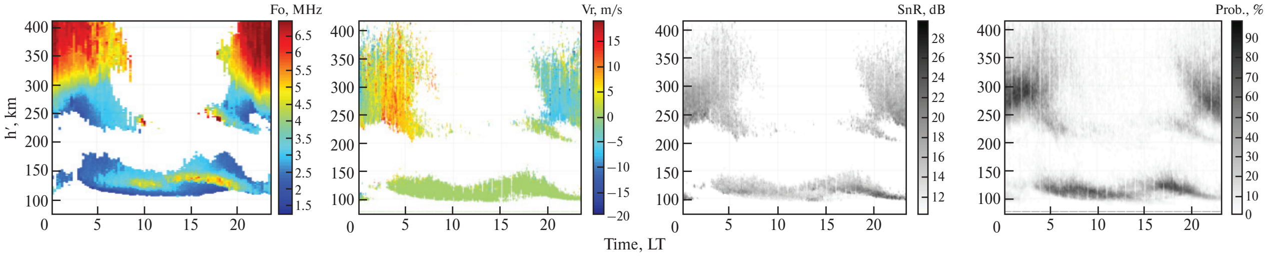


Akademik Vernadsky station, December 2017

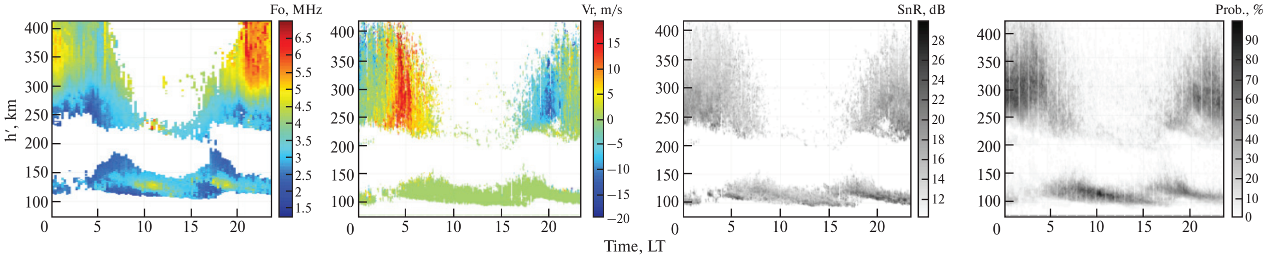


2018

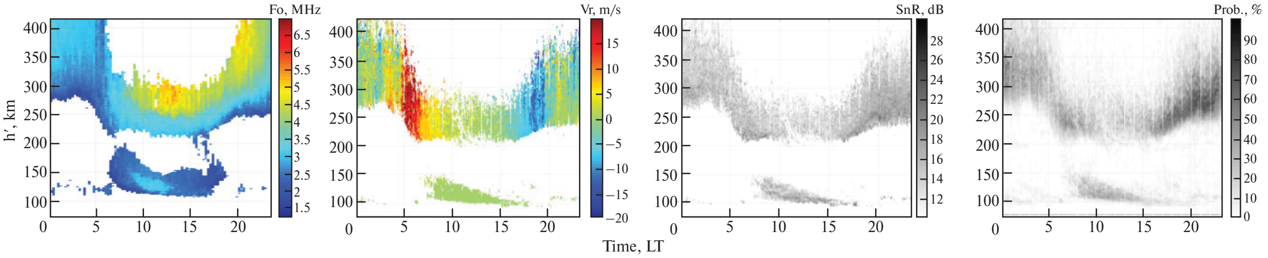
Akademik Vernadsky station, January 2018



Akademik Vernadsky station, February 2018



Akademik Vernadsky station, March 2018



Akademik Vernadsky station, April 2018

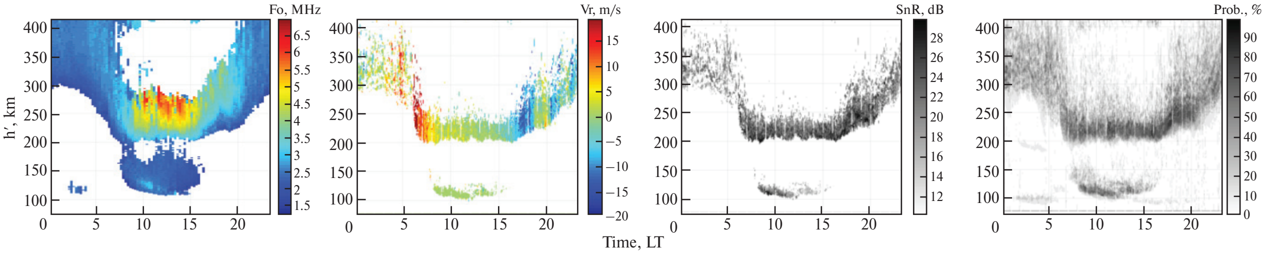


Figure 1. Median HT-diagrams of (from left to right) frequencies reflected from the ionosphere (plasma frequencies), vertical plasma velocity, signal-to-noise ratio, and probability of the reflected signal presence over the Akademik Vernadsky station from April 2017 to March 2018 (from top to bottom) according to data of ionospheric sounding at the Akademik Vernadsky station

in the evening, the plasma velocities are negative in all the height range.

It is worth noting also that HT-diagrams are a good tool for studying the regular behavior of the sporadic E layers (E_s) of the ionosphere (heights below 150 km). The maximum of their occurrence is observed during summer months (Fig. 1, all columns). However E_s is present in all seasons mostly during the daytime. Two downward trends per day in the E_s heights can be recognized on HT-diagrams in summer (Fig. 1, all columns, December 2017 — February 2018). Some authors associated this behavior with the impact of tidal waves on the E_s (e.g. Haldoupis, 2006).

Vertical velocities on the E_s layer heights estimated by the new ionosonde are equal to zero at all times. Taking into account the resolution of the instrument, one may easily conclude that vertical velocities of the E_s layer are usually smaller than 10 m/s.

3.2 Automatic estimation of the maximum usable frequency

The considered median HT-diagrams of plasma frequencies can be used for alternative calculation of maximum usable frequency (MUF) for radio links of the specified length without additional manual or auto-scaling. The currently used approach is to estimate median values for foF2 and M(3000) parameters from the scaled of ionograms. The value of MUF(3000) is suggested as a product of fo F2 and M(3000). Actually, the product of two median values is not equal to the median value of the product.

Therefore, it seems to be better to estimate median values of MUF(D) for specified distance D using raw ionograms. In this case, the value of foF2 should be recalculated into MUF value for each virtual height and specified distance D. That can be done using the similar triangle theorem (Davies, 1990). Estimated values of MUF(D) for each virtual height can be used for building the HT-diagrams of MUF(h, D) (example is shown at Fig. 2, left panel). For HT-diagram the value of MUF(D) can be found as a maximum in height profile for each time domain. Finally, the median value of MUF(D) can be calculated using the set of MUF(D) values calculated for specified time.

The examples of estimations of MUF(D) for the distances from 0 till 3000 km for the April 2018 using

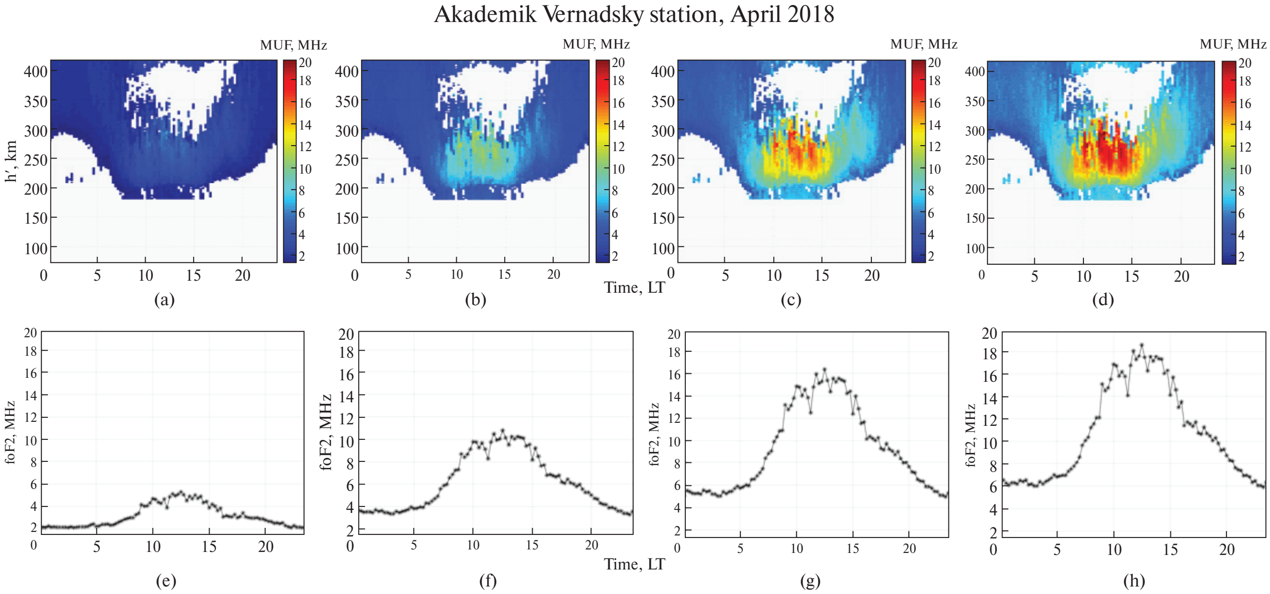


Figure 2. Examples of automatic recalculation the MUF for reflection from specified virtual height in the form of HT-diagrams (a–d), and as a function of time (e–h) for the radio paths of the length: (a), (e) 0 km; (b), (f) 1000 km; (c), (g) 2000 km and (d), (h) 3000 km

the median HT-diagram of plasma frequencies are shown in Fig. 2. The left panel shows the median values of MUF (h, D) for each virtual height. Using this representation we can estimate the median value of the virtual height providing reflection on the radio link of length D at the specified frequency. Right panels demonstrate the diurnal variation of median MUF(D) calculated using the technique mentioned above. Those calculations were made for the model of plane stratified ionosphere. Nevertheless the Earth's curvature was taken into account to estimate the angle of incidence of the HF wave on the ionosphere. The average difference of 0.6 MHz between foF2 and fxF2 for the Akademik Vernadsky station location was considered, so the estimations of MUF for wave of O-polarization are shown in Fig. 2.

3.3 Observation of travelling ionospheric disturbances

As it was shown earlier (e.g., Zalizovski, 2011), Antarctic Peninsula region is a very suitable place to study the impact of neutral atmosphere on the upper atmosphere. An effective transport agent for that is atmospheric gravity waves (AGW) manifesting themselves as travelling ionospheric disturbances in the near-Earth plasma. Therefore, the new tools for estimating the parameters of the AGW/TID in this region could make a significant contribution to the study.

As mentioned above, the 5-minute sampling rate of the new ionosonde was selected with a goal to detect and reconstruct characteristics of AGW/TID over the Akademik Vernadsky station. Let us consider the TID observed on HT-diagrams of both ionosondes operating at the Akademik Vernadsky station at a certain moment of time (Fig. 3). As one can see, quasi-periodic variations associated with TID are observed in both virtual height (top panel) and DFS (bottom panel). The vertical velocity of TID can be estimated from variations of virtual heights. In the case shown by black line (Fig. 3, upper panel) the period of variation is equal to ~1 hour and downward phase velocity is equal to ~50 m/s. It means that the group velocity has an upward direction.

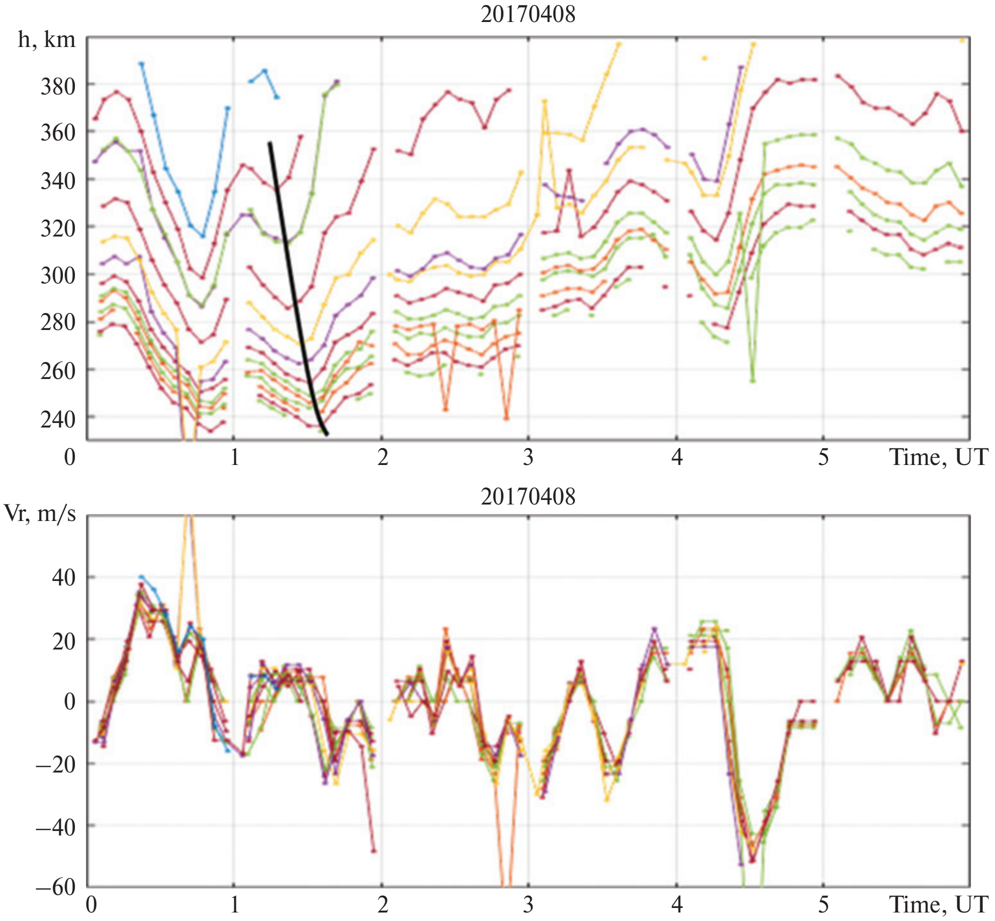


Figure 3. Example of TID observed at the Akademik Vernadsky station on 8 April 2017 in variations of virtual heights (top panel) and DFS converted to vertical speed (bottom panel). Different curves correspond to frequencies from 1.60 to 3.76 MHz. Black line at the top panel shows the vertical movement of the equal phase surface

Comparison of the top and bottom panels allows us to conclude that TID are observed in both variations. However, the waves with periods 1 hour and more are better observed in height variations, and waves with periods less than 1 hour are better observed in variations of DFS.

It should be noted that we have two parameters connected with the motion of the ionospheric plasma. The first one is the change of virtual height of reflecting surface shown at the top panel in Fig. 3. The second is the vertical plasma velocity estimated using DFS for each virtual height of reflection point that manifests the group speed of the waves (the bottom panel in Fig. 3).

The main parameter measured by an ionosonde is the virtual height h' of the reflection point for the signal calculated as $h' = \frac{c\tau}{2}$, where c is speed of light and τ is the measured time delay of the reflected signal. It could be expressed as:

$$h' = c\int_{0}^{h_r} dz \big/ V_{gr} \ ,$$

where h_r is a true height of signal reflection, V_{gr} is a group velocity. Since V_{gr} in the ionospheric plasma is smaller than speed of light c (Davies, 1990), virtual height h' is bigger the true h_r. The change of virtual heights associated with TID can be estimated as a time derivative of the $h^{/}$ variations shown on the top panel of Fig. 3 as:

$$V_r^{//} = -\frac{dh^{/}}{dt} = -\frac{c}{2}\frac{d}{dt}\int_L \left(\frac{1}{V_{gr}(l)}\right) dl \, .$$

Expressing the group velocity through the refractive index, we obtain:

$$V_r^{//} = -\frac{1}{2}\frac{d}{dt}\int_L \left(\frac{1}{n(l)}\right) dl \, , \tag{1}$$

where n — refractive index, L — trajectory of the signal (upward and back).

On the other hand, we have direct measurements of DFS F_D of the same signals that could be described as (Davies, 1990):

$$F_D = -\frac{f}{c}\frac{dP}{dt} = -\frac{f}{c}\frac{d}{dt}\int_L n(l)dl \, ,$$

where f is the carrier frequency. We convert DFS F_D to virtual plasma velocity (shown at the bottom panel of Fig. 3) as $V_r^{/} = \frac{1}{2}\frac{F_D c}{f}$, in other words:

$$V_r^{/} = -\frac{1}{2}\frac{d}{dt}\int_L n(l)dl \, . \tag{2}$$

By comparison of (1) and (2) it can be concluded that the difference between two values $V_r^{/}$ and $V_r^{//}$ of velocity estimation depends on the dynamics of the refractive index along the signal trajectory. In the case of the layer moving as a whole, or if the layer can be considered a thin reflecting surface, the time derivate of the refractive index along the trajectory is zero, so $V_r^{/}$ and $V_r^{//}$ depend on the derivate of trajectory length, or on the height of the reflection point h_r for the vertical propagation. In this case $V_r^{/}$ and $V_r^{//}$ should be equal or close to each other, which means the approximation of TID as a wave on a thin reflecting surface can be used as the most adequate. In the opposite case, when the time derivate from refractive index along the trajectory is not zero and cannot be neglected, the values of $V_r^{/}$ and $V_r^{//}$ are significantly different. This means the approximation of TID as a three-dimensional plasma density wave traveling through a real ionospheric layer should be used as the more appropriate.

4 Conclusions

The simultaneous operation of two different ionosondes at the Akademik Vernadsky station allows us to significantly expand the amount and quality of the objective information about the ionosphere behavior over the Antarctic Peninsula.

The technique to construct median HT-diagrams described in this paper allows to analyze the variations of the averaged characteristics not only in time but also in height. Median HT-diagrams can be used to study regular processes in the ionosphere. They can be also useful for comparison of the ionosphere conditions between different geographical locations or time intervals, for automatic estimation of MUF for the radio links of the specified length, as well as information about the background variations that can be taken into account for estimating the parameters of ionospheric disturbances.

Combining the data sets of two different ionosondes at the Akademik Vernadsky station can be considered as a new additional powerful tool for studying the travelling ionospheric disturbances over the Antarctic Peninsula. For example, the comparison of the variation of DFS and virtual heights can be used to select the most suitable model describing the specific type of TID observed.

Author contributions. AZ: idea and draft writing. OK: software development and data processing. AK: ionosonde initial design and development. SK: RF frontend. YuYa: experiment concept. OCh, AZ, YuYa: data comparison, manuscript drafting and editing. All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Допплерівське вертикальне зондування іоносфери на Українській антарктичній станції «Академік Вернадський»

Реферат. Мета роботи полягає у наданні технічної інформації щодо допплерівського вертикального зондування іоносфери, розпочатого на Українській антарктичній станції «Академік Вернадський» у 2017 році; опису методики обробки та візуалізації даних вертикального зондування іоносфери у вигляді медіанних висотно-часових діаграм; демонстрації можливостей допплерівського зондування іоносфери на прикладі результатів, що отримані протягом першого року роботи системи на станції «Академік Вернадський», а саме, фонових варіацій параметрів іоносфери протягом року, а також реєстрацій рухомих іоносферних збурень (РІЗ). В роботі застосовано наступні методи: класичне вертикальне зондування іоносфери за допомогою іонозонду IPS-42, що використовується на станції «Академік Вернадський» з 1982 року; допплерівське вертикальне зондування іоносфери за допомогою портативного іонозонду, що був створений у співробітництві між Міжнародним центром теоретичної фізики ім. Абдус Салама (Abdus Salam International Centre for Theoretical Physics, ICTP) і Радіоастрономічним інститутом Національної академії наук України (РІ НАНУ); побудова висотно-часових діаграм параметрів іоносфери, отриманих за допомогою обох іонозондів; а також оригінальна методика розрахунку медіанних висотно-часових діаграм як фонових середньомісячних характеристик іоносфери. На прикладі медіанних висотно-часових діаграм показано сезонно-добові варіації плазмових частот, вертикальних швидкостей плазми, а також відношення сигнал-шум та ймовірності реєстрації відбитих сигналів за перший рік сумісної роботи двох іонозондів. Наведено особливості та розглянуто сфери потенційного застосування медіанних висотно-часових діаграм. Так, висотно-частотні діаграми можуть бути використані для автоматичного розрахунку варіацій максимальних застосовних частот (МЗЧ) для радіозв'язку на лінії заданої протяжності. Наведено приклади реєстрації РІЗ у варіаціях діючих висот відбиття, а також допплерівських зсувів частоти (ДЗЧ) сигналів. Показано, що порівняння проявів РІЗ у варіаціях діючих висот та ДЗЧ можна використовувати для вибору більш адекватної моделі РІЗ: ідеально відбиваючої схвильованої поверхні або хвиль об'ємної щільності плазми, що поширюються крізь іоносферний шар. У якості висновку можна зазначити, що одночасна робота двох іонозондів на станції «Академік Вернадський» дозволила суттєво розширити об'єм та якість об'єктивної інформації про стан іоносфери над Антарктичним півостровом.

Ключові слова: іоносфера, допплерівське зондування, іонограма, медіанне значення, висотно-часова діаграма, рухомі іоносферні збурення