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STUDY OF IONOSPHERIC IRREGULARITIES USING HF RADARS

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Abstract. We present the results of ionospheric irregularities studies using HF radar data (SuperDARN type) in the Institute of Solar-Terrestrial Physics SB RAS. We focus on two topics. The first topic is related to the study of field-aligned ionospheric irregularities (FAI) of decameter scale. The data obtained by the EKB HF radar during the November 7-11, 2017 geomagnetic storm is presented. It is shown that the ionospheric scatter observed by the radar moves equatorward during the main phase of the storm accompanied with the well-known expansion of the auroral oval and its movement to lower latitudes. The second topic is devoted to the study of medium-scale traveling ionospheric disturbances (MSTIDs) and their relationship with internal gravity waves (IGW) propagating in the Earth's upper atmosphere. The results of statistical analysis of MSTID parameters obtained from the EKB HF radar data are presented, and the possibilities of their use for estimating the neutral wind velocity at ionospheric heights are discussed.

Introduction

HF radars have been intensively used in the ionosphere studies since about the mid-1990s, when the corresponding electronic equipment was developed and SuperDARN achieved its official status [1]. Firstly the aim was to study auroral ionosphere, however further SuperDARN was expanded to subauroral and mid-latitudes. HF radar emits radio waves and registered backscattered echo from ionospheric irregularities and/or rough ground surface. Narrow in azimuthal plane antenna pattern (~3.5°) allows accurate mapping the echoes located at distances up to several thousand kilometers from the radar, whereas high temporal resolution (of about 2 minutes and less) allows to study highly dynamical processes in the atmosphere.

Radars are most effective in the network, when it is possible to reconstruct plasma convection maps in the extensive region of polar, auroral, and subauroral ionosphere. At the same time, information on the dynamics of the high-latitude ionosphere can also be obtained from the data of individual HF radars. In Russia, there are currently two SuperDARN-like HF radars (but not included in SuperDARN): in Yekaterinburg (EKB; 56.4ºN, 58.5ºE) and Magadan (MGW; 60.0ºN, 150.7ºE). The paper presents recent results of ionospheric irregularities dynamics studies based on the EKB HF radar data obtained at ISTP SB RAS. The first part is devoted to the study of decameter-scale field-aligned irregularities (FAI), originated within the polar, auroral, and subauroral regions of the ionosphere. The second part concerns the studies of mid-latitude medium-scale traveling ionospheric disturbances (MSTIDs; the wavelength is of the order of several hundreds of kilometers).

Ionospheric irregularities during the November 7-11, 2017 geomagnetic storm

One of the features of the high-latitude ionosphere is a presence of FAIs. Scattering of HF waves by FAI has a pronounced aspect effect: the largest amplitude of the scattered echo should be expected when HF wave vector is perpendicular to geomagnetic field lines. Under such conditions, radar registers a strong coherent HF echo, and is able to determine location of scattering irregularities and their Doppler velocity (or more precisely the FAI horizontal velocity component along the sounding direction). In the standard operational mode the EKB HF radar scans 16 independent sounding directions - beams and, thus, allows localizing ionospheric echoes and studying their dynamics within the wide radar field-of-view (FOV). FAI dynamics is caused by plasma convection in crossed electric and magnetic fields, and therefore, it reflects the structure and dynamics of the magnetosphere-ionosphere-thermosphere system.

Let us consider the dynamics of ionospheric echoes during the November 7-11, 2017 moderate geomagnetic storm. Fig. 1a shows the behavior of DST and Kp indices during November 6-7, 2017. Fig. 1b presents the Doppler velocity of the ionospheric echoes registered on beam #2 (Doppler velocity is shown by color according to the color scale on the right). The vertical axis shows the magnetic latitude (MLAT) where scattered echoes came from. The red color corresponds to the propagation direction away from the radar, and the blue color corresponds to the propagation to the radar. Fig. 2 presents the ionospheric echoes mapped within the EKB FOV for different UT. As one can see from Fig. 1a, the initial phase of the storm lasted from 02:30 to 08:00 UT. During the initial storm phase, a positive deviation of DST index is observed, and Kp index increases from 1 to 3. Approximately one hour after the storm set on, at 03:45 UT (~8 LT), intense ionospheric echoes were observed on western beams #0-3 at about 73°MLAT (Figs. 1b and 2a). The Doppler velocity was negative, so the irregularities moved northward. Around 07:00, the scatter region expanded eastward onto beams #4-7, however, the Doppler velocity was positive, which means that irregularities propagate towards the radar (see Fig. 2a-b) [2].

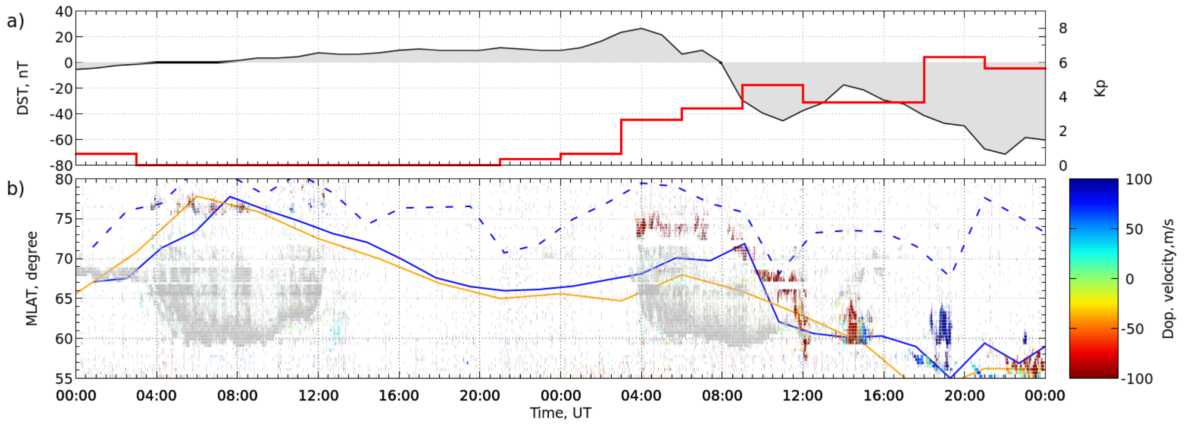

Figure 1. DST (black curve) and Kp indexes (red color) during the November 7-11, 2017 moderate geomagnetic storm (a). MLAT-UT- Doppler velocity plot of the ionospheric scatters observed by the EKB HF radar on beam #2 (b). Doppler velocity is shown by color according to the color bar on the right. The color lines are the auroral oval boundaries according to IRI-2016 (TIMED/GUVI) model (orange) and GUVI (DMSP-SSUSI) model (blue). Solid and dashed lines correspond to the equatorial and polar boundary respectively.

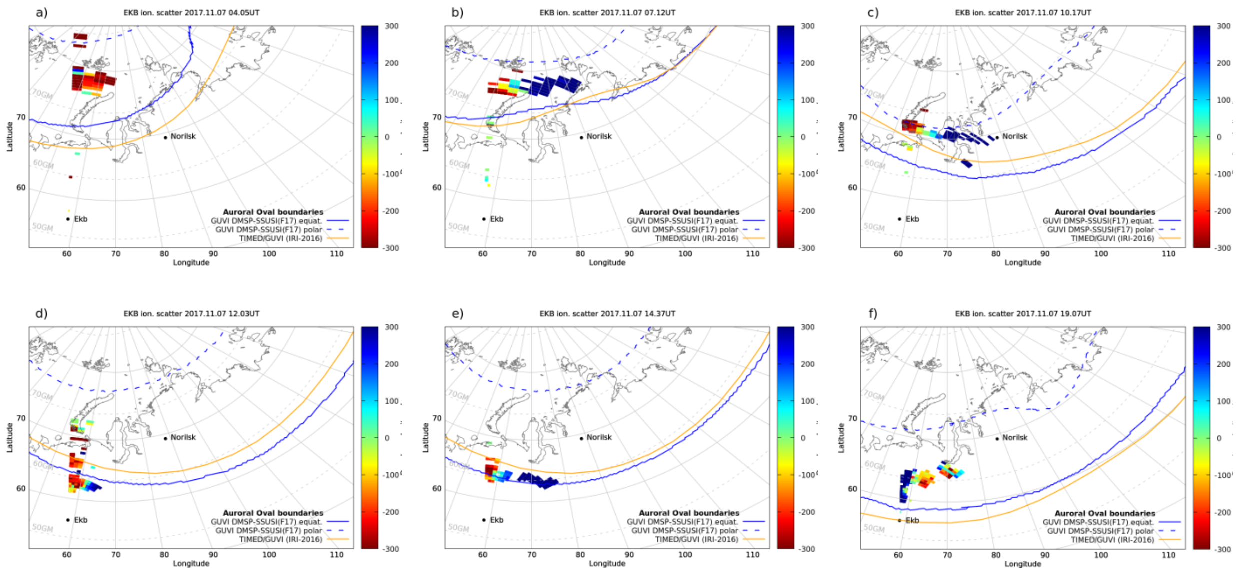

Figure 2. Location of the ionospheric scatters (with SNR > 6 dB) for (a) 04:05, (b) 07:12, (c) 10:17, (d) 12:03, (e) 14:37 и (f) 19:07 UT. Doppler velocity is shown by color according to the color bar on the right. The color lines are the boundaries of the auroral oval (the legend is the same as on Fig. 1b).

The main phase of the storm from approximately 08:00 (DST=0, Kp=3) on November 7 to 01:00 on November 8, 2022 (DST=-73, Kp=6) was accompanied by a shift of the scatter region to the lower latitudes. On beam #2, the scatter region shifted from ~73°MLAT at 8:15, to ~65°MLAT at 11:30, and further to ~57°MLAT at 12:15 (Fig. 1b). From 12:20 the ionospheric echoes are practically absent and reappear from 13:30 to 15:30 (Fig. 1b) on beam #2 in the latitude range 59-65°. At 17:40-19:30, another scatter region is observed (Fig. 1b) with the Doppler velocity for this region positive on beam #2 and negative on beam #12. This can be explained by that the echoes came from the eastern auroral electrojet on beam #2 and from the western auroral electrojet on beam #12. Further, localized scatter regions with their equatorial boundary shifting up to ~54°MLAT at ~21 UT are observed. It can be assumed that intense ionospheric irregularities moved equatorward and left the EKB FOV after 19 UT.

The described dynamics of ionospheric scatter during geomagnetic storms is well known and accompanied with the expansion and shift of the auroral region towards mid-latitudes [3, 4]. The blue curves in Fig. 1b and 2 show the position of the polar (dashed) and equatorial (solid) boundaries of the auroral oval as obtained from the GUVI model and DMSP data (https://ssusi.jhuapl.edu/gal_edr-aur_cs). The orange line also shows the equatorial boundary of the auroral oval calculated using the TIMED/GUVI model included in IRI-2016. It is clearly seen that the location of the scatter regions is mainly within the boundaries of the auroral oval. However, as follows from Fig. 1b, 2d, and 2e (for TIMED/GUVI model) ionospheric echoes can also come from subauroral latitudes. This is also confirmed by the observations of subauroral polarization streams (SAPS) by SuperDARN HF radars (see, for example, [5]). In general, observation of ionospheric echoes requires, firstly, the presence (generation) of intense decameter-scale ionospheric irregularities and, secondly, the aspect scattering condition fulfillment, which in turn is determined by the radio wave propagation effects (refraction and absorption) and geomagnetic field. In [4], location of the scatter regions observed on the EKB HF radar during the May 28, 2017 geomagnetic storm was compared with the position of R1/R2 regions of field-aligned currents (FACs; also known as Birkeland currents) as seen from AMPERE data. It is shown that FACs dynamics satisfactorily correlates with the appearance of scatter regions. This may indirectly indicate that intense generation of ionospheric irregularities occurs within R1/R2 current regions. However, periods of strong HF absorption observed by riometer within the EKB HF radar FOV also correlate with complete or partial disappearance of ionospheric echoes [2, 4]. Thus, equatorial boundary of the ionospheric scatter observed by HF radar cannot be a reliable proxy for the location of the auroral oval.

Study of mid-latitude MSTIDs

In Fig. 1b, in addition to the direct ionospheric scatter, the gray color shows the echoes scattered by earth's rough surface (ground scatter). In contrast to the ionospheric scatter, ground scatter is characterized by a relatively regular diurnal-seasonal behavior determined by regular variations in the critical frequency and maximum height of the F2 layer of the ionosphere. When a traveling ionospheric disturbance (TID) propagates within radar FOV, modulation of ground scatter parameters occurs. For example, there may be variations in the minimum oblique range which corresponds to the HF skip distance. We develop a technique for TID's parameters determination, such as propagation azimuth, apparent horizontal velocity, period, wavelength, and amplitude, based on a cross-correlation analysis of similar variations on different beams of single HF radar.

In [6], we studied the diurnal-seasonal dependencies of MSTID parameters using the HOK and EKB HF radars data. It is shown that there are several preferential azimuths of MSTIDs propagation depending on local time and associated with the horizontal neutral wind behavior at the heights of MSTID propagation. For illustration Fig. 3a shows local time dependence of the observed MSTID azimuth occurrence for winter seasons (November-February) as obtained from the EKB HF radar data during the period from 2013 to 2021. As seen the preferred direction of MSTID propagation is 90-130° during the daytime hours, 210-250° in the pre-dawn, and 280-20° in the pre-sunset respectively.

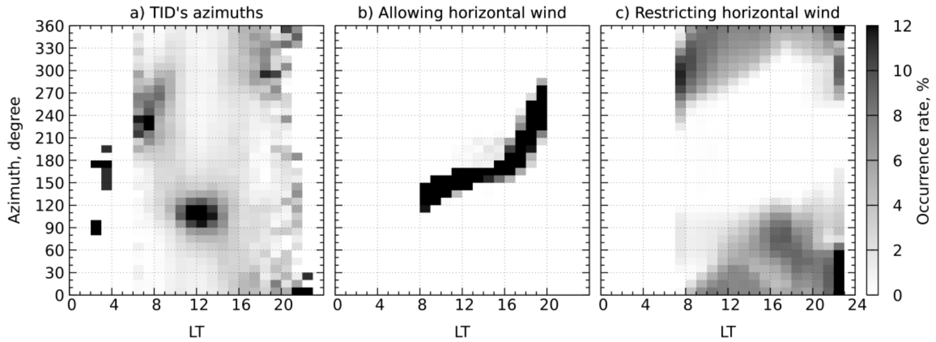

Figure 3. Relative occurrence rate of the observed MSTID azimuth during winter (November-to-February) for 2013-2021 (a). Expected relative occurrence rate for the headwind at HF reflection height (b) and for the tailwind within the height range from 10 km to the HF reflection height (c).

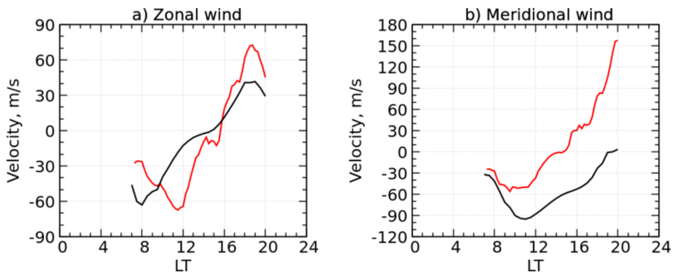

Figure 4. Diurnal dependence of zonal (a) and meridional (b) components of the horizontal neutral wind calculated based on the Fig. 3a data (red curve) and by HWM14 model at the HF reflection height.

The one possible origin of MSTIDs is internal gravity waves (IGWs) propagating in the Earth's atmosphere. According to the IGW theory the observed MSTIDs preferred directions can be explained by interaction between IGW and horizontal neutral wind. A headwind leads to an IGW strengthening, and a tailwind, on the contrary, to an IGW weakening, or even to its destruction. Fig. 3b shows the diurnal dependence of the amplifying wind (headwind) occurrence at the HF reflection heights, and Fig. 3c shows the similar dependence for the attenuating wind (tailwind) within the entire atmosphere from the ground up to the HF reflection heights. The calculations were performed using HWM14 model for the same periods and heights when MSTIDs were observed by the EKB radar (see Fig. 3a). Comparing Fig. 3a, 3b, and 3c, one can conclude that the majority of MSTIDs lies in the areas where the attenuating wind is absent while the strengthening one, on the contrary, is well developed. Thus, the majority of MSTIDs is indeed could be considered as manifestation of IGWs.

The above discussion suggests trying to restore the parameters of the neutral wind from the observed MSTID statistical distributions. Paper [7] proposes a method for estimating the horizontal neutral wind azimuth using the observed MSTID statistics based on HF radar data. However, we can go further if we use a priori information about the IGW median wavelength obtained, for example, in [8] from the joint observations by the Irkutsk incoherent scatter radar and Digisond. Fig. 4 presents diurnal dependence of zonal and meridional neutral wind components reconstructed from the data of Fig. 3a (red curve) and calculated using HWM14 model (black curve). One can see that the reconstructed parameters agree satisfactorily with the modeled ones. At the same time, differences are also visible, which can be explained by some features of the neutral wind that are not described by HWM14 model. Another possible explanation is the fact that the data of Fig. 3a also could contain some amount of MSTIDs of different than IGW origin [8].

Summary

The paper presents a brief overview of the recent researches provided by ISTP SB RAS based on the data of Russian HF radars. We show the possibilities of the HF radars for studying the dynamics of ionospheric irregularities of different origin and for developing new methods for atmospheric processes studies. Further expansion of the Russian HF radars network will provide more information about the auroral, subauroral, and mid-latitude ionosphere in the future.

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