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OBSERVING MAGNETOSPHERIC WAVES PROPAGATING IN THE DIRECTION OF ELECTRON DRIFT WITH EKATERINBURG DECAMETER COHERENT RADAR

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Abstract. This paper deals with Pc5 magnetospheric pulsations featuring positive azimuthal wave numbers registered with the mid-latitude coherent decameter radar located near Ekaterinburg (EKB). The azimuthal wave numbers are determined using adjacent high time resolution beams directed toward the magnetic pole. Approximately 13 % of all steady waves registered with the radar propagate eastward. We have examined ten cases of wave observations with both small and high positive wave numbers, which occurred between April 2014 and March 2015. We performed a wavelet analysis of the data sets, estimated wavelength in radial direction for four cases, and determined meridional phase propagation direction. In three cases, the results are consistent with field line resonance behavior. However, in the majority of the studied events wave frequencies are considerably lower than those of field line resonance, which were derived from satellite data on magnetic field and particle density. These waves may be classed with the drift-compressional mode.

Keywords: ULF waves, radar, magnetosphere.

INTRODUCTION

An important parameter of ULF wave in the magnetosphere, which determines its properties and nature of resonant interaction with charged energetic particles, is the azimuthal wave number *m*. It represents the number of wavelengths, which fits the annular path of wave propagation around Earth to the azimuth direction. The azimuthal wave number determines the energy of particles involved in the drift resonance with the wave. Waves with sources external and internal with respect to the magnetosphere are thought to have azimuthal wave numbers of different orders. So, waves with small *m*, which have a predominantly toroidal polarization, are associated with a fast magnetic sound propagating from the magnetopause or from the solar wind into the magnetosphere and exciting Alfvén waves on the magnetic shells, frequencies of eigenoscillations of which coincide with the frequency of the sound [Chen, Hasegawa, 1974; Southwood, 1974]. Waves with large azimuthal wave numbers (usually $|m|>20$) are driven by intermagnetospheric processes. These waves are often identified as poloidal Alfvén modes, although the separation into toroidal and poloidal waves according to polarization is rather arbitrary because oscillation components may be commensurable; besides, waves can undergo a transformation from toroidal into poloidal [Klimushkin et al., 2004].

There are several ways of determining the azimuthal wave number from ground and satellite data [Zong et al., 2017]. The most direct of them is to determine the wave phase difference between two (or more) longitudinally spaced measurement points:

$$m=\frac{\Delta\varphi}{\Delta\lambda}, \quad (1)$$

where $\Delta\varphi$ is the difference between wave phases at measurement points, and $\Delta\lambda$ is the difference between their longitudes. Positive values of *m* correspond to eastward wave propagation; and negative, to the westward one. Measurement points can be located both in the magnetosphere, onboard satellites, and in Earth's surface. Because of the ionospheric shielding of waves with large azimuthal wave numbers, it is almost impossible to detect them with ground-based magnetometers. It is, however, possible to detect such waves with radars [Yeoman et al., 2012], which are convenient for the study of the spatial structure of oscillations in the magnetosphere.

In experiments, westward waves with large *m* are usually observed ($m<0$). Such waves can effectively interact with high-energy protons, whose drift velocity is also westward [Zong et al., 2017]. The eastward waves with $m>0$ are relatively rare [Eriksson et al., 2006; Le et al., 2011]. These waves can effectively interact with electrons whose drift velocity is eastward, as well as the phase velocity of the waves with $m>0$. Energetic electrons can generate waves with $m>0$ due to the drift resonance. Indeed, as shown in [James et al., 2013; Hori et al., 2018], waves with positive *m* are observed to the east of substorm injections. This suggests that they were generated by energetic electrons injected during substorms. The nature of eastward propagating azimuthally small-scale waves is uncertain. In most cases, they are associated with Alfvén waves; Kostarev and Mager [2017] have, however, shown that Pc5 drift compressional waves can also propagate in the electron drift direction.

Takahashi et al. [1987] have suggested that the waves propagating eastward from the viewpoint of a stationary observer outside the geostationary orbit propagate westward relative to the proton cloud drifting to the east under the action of an electric field at a velocity higher than the phase velocity of the wave.

As for the waves with small azimuthal wave numbers, since their sources are in the solar wind or related to its interaction with the magnetosphere, they generally propagate in a direction from the subsolar point [Mazur, Chuiko, 2011, Mazur, Chuiko, 2013].

The paper examines a number of observations of magnetospheric waves with positive azimuthal wave numbers. We employed a mid-latitude coherent radar located near Ekaterinburg. The oscillations occurred during 2014 and three months of 2015. We have examined the direction of their propagation and features of polarization. Some of these data have partially been used in [Chelpanov et al., 2018], where frequencies of waves observed with the radar were compared with frequencies of the Alfvén mode. We also take these results into account in the analysis.

EQUIPMENT AND ANALYSIS

The EKB radar is similar to SuperDARN radars. The recording of signals reflected from field-aligned ionospheric irregularities allows us to estimate their velocity in the direction of the radar beam. Three of its beams work in a high-frequency mode providing a time resolution of 18 s. They receive a signal from a 54°–78° geomagnetic latitude range. This field of view is divided into a number of range gates, 45 km each. On the assumption that the reflection point belongs to a certain range, we determine the distance between the point and the radar. Ionospheric plasma velocity variations are associated with electric field variations, which in turn are caused by electromagnetic waves in the magnetosphere. In this paper, we use beams whose direction is close to the magnetic meridian. This means that the plasma velocity variations recorded using the beams are connected with the poloidal magnetic field component since the direction of plasma motion is perpendicular to the electric field, which in turn is perpendicular to the magnetic field. The plasma velocity variations for the cases we describe are shown in Figure 1.

In the analysis of radar data, it is important to identify signals reflected from the ionosphere and from ground and water surfaces because only the former contain information about electromagnetic oscillations in the magnetosphere available for the analysis. Besides the differences in the Doppler shift and spectral width, the groundscatter for the EKB radar exhibits a special latitude dependence on MLT [Berngardt et al., 2015]. At night, they are displaced by 2000–3000 km from the radar. This suggests that the small-scale plasma velocity variations are caused by magnetospheric waves.

The presence of adjacent beams with high time resolution makes it possible to examine the structure of waves in the azimuth direction. The initial data were interpolated in order to equalize time intervals between readings. Then, we employed a high-pass filter with a cutoff frequency of 600 s. For the cross-spectral analysis of the data, we used the Marlet wavelet transform

$$W(\omega,\tau)=\sqrt{\omega}\sum_{j=1}^{N}x(t_j)e^{i\omega(\tau-t_j)-(\tau-t_j)^2/2T^2}. \qquad (2)$$

Here ω is the cyclic frequency; τ is the time shift; $x(t_j)$ are signal values in N discrete time values, where j=1, 2, ..., N; $T=2\pi/\omega$ is the period. The difference between signal phases Δφ, received in different beams, is equal to the phase of the complex value

$$W_{12}(\omega,\tau)=W_1(\omega,\tau)W_2^*(\omega,\tau), \qquad (3)$$

where W_1 and W_2^* are the wavelet transform and the complex-conjugate wavelet transform for signals in adjacent beams. Knowing the difference in longitude between signal reflection points Δλ, which for the events of interest varies from 0.7° to 4.2° depending on the selected pair of beams and the distance from the radar, from (1) we can find the azimuthal wave number m.

To determine parameters of oscillations, we use their common power along two beams

$$F_{12}(\omega,\tau)=F_1(\omega,\tau)F_2(\omega,\tau).$$

Here

$$F(\omega,\tau)=\frac{2|W|}{\sqrt{\omega}n(\omega,\tau)}, \qquad (4)$$

where the normalizing factor is

$$n(\omega,\tau)=\sum_{j=1}^{N}e^{-(\tau-t_j)^2/2T^2}. \qquad (5)$$

Maxima of the common power are at those points of the frequency – time plane where the oscillations are most intense. The azimuthal wave number was determined for the oscillatory harmonics whose duration exceeded three periods. This limitation was put to select relatively stable oscillations from features of the wavelet in use. For each event, we chose the pair of beams that had the minimum amount of missing data.

During the observation period from January 2014 to March 2015, we found 39 cases of recordings of ULF oscillations with the radar. In some cases, we observed oscillations with one fundamental frequency. The spectral structure of oscillations in other cases was more complex – they comprised two or three oscillation harmonics with different frequencies. Using the above criterion of duration of oscillations, we can select only 74 stable oscillatory harmonics. In eight of the 74 cases, we recorded oscillations with positive azimuthal wave numbers; in two events, we observed two harmonics with positive m. We have acquired data on ten eastward propagating waves. Thus, among stable oscillations recorded with the radar, ~13 % of waves have positive azimuthal wave numbers. Basic parameters of these oscillations – frequency and wave number, as well as date and time of recording – are listed in Table 1. To specify the wave propagation direction, we carried out a cross-correlation analysis.

All waves with positive m were observed within 23:30–06:40 MLT. Some events lasted less than one hour, predominantly ~20 min. The oscillations were recorded within the 58°–66° geomagnetic latitude, which

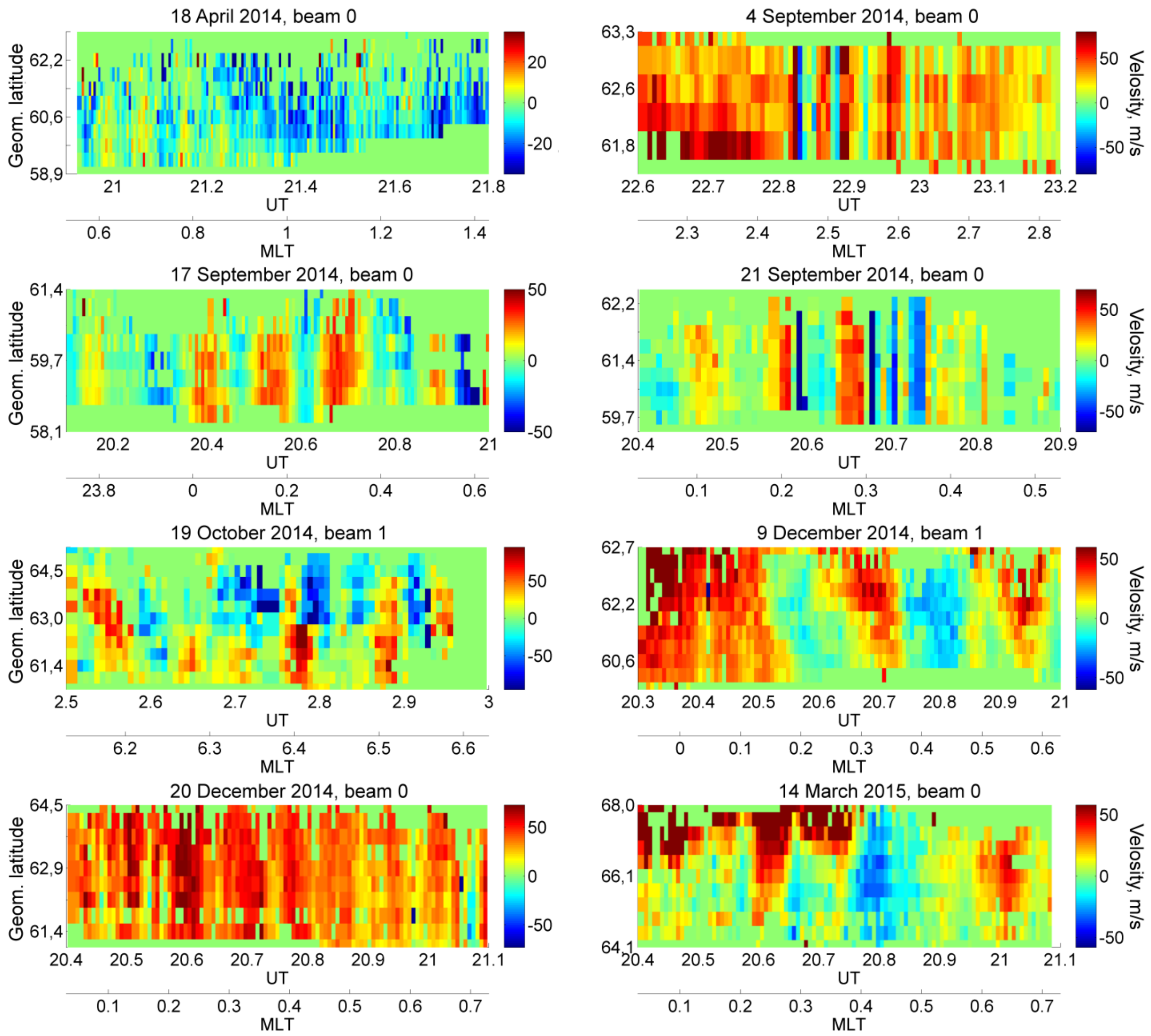

Figure 1. Plasma velocities recorded by the radar. Positive values correspond to the direction of the radar

Table 1

Date	UT	*f*	*m*
April 18, 2014	21:00–21:20	3.7	22
September 04, 2014	22:40–23:00	4.8	25
September 17, 2014	20:20–20:45	2.5	5
September 21, 2014	20:25–20:50	3.0	27
October 19, 2014	02:45–03:00	3.4	17
December 09, 2014	20:35–20:55	3.3	37
December 09, 2014	20:20–20:45	2.4	143
December 30, 2014	20:30–21:00	3.4	6
March 14, 2015	19:50–20:10	3.1	6
March 14, 2015	20:30–20:50	2.1	2

corresponds to magnetic shells 3.8–6.5 (according to the IGRF model).

The duration of observations of oscillations often does not exceed the number of periods, and frequency changes during this time are usually small compared to the spectral resolution. Therefore, when processing results, to each oscillation harmonic we assigned a single frequency determined at a maximum oscillation power. In a similar way we estimated azimuthal wave numbers of oscillatory harmonics. Note that the determination of coordinates of the point of signal reflection from an ionospheric irregularity is not accurate; the error may be up to 200 km in the direction of the radar beam, so the systematic error in determining the azimuthal wave number may reach 25 %.

Frequencies of the oscillations we consider are within 2–6 MHz. In two cases, they are close to frequencies of the Alfvén field line resonance, estimated from satellite data on the magnetic field and particle density in the observation sector. To determine them, we adopted a dipole magnetic field model and the power law of field-aligned particle distribution (for more details see [Chelpanov et al., 2018]). On September 4, 2014, the frequency of the oscillatory harmonic with positive m was approximately equal to 4.8 MHz, while the frequency of the field line resonance in the observation sector was estimated at 4.1 mHz; on September 21, 2014, the frequencies obtained from radar and satellite data were 3 and 2.7 MHz respectively. In view of the uncertainties caused by the models in use, the oscillations recorded with the radar in these cases may be the field line resonance. For three cases there are no data on magnetospheric plasma parameters because during the observations there were no satellites on suitable magnetic shells in the longitudinal sector of the radar. In three other cases, in two of which two harmonics with m>0 were observed, oscillation frequencies were several times lower than Alfvén resonance frequencies estimated from satellite data. It therefore seems unlikely that they can be related to Alfvén waves.

Figure 2 shows oscillations with a positive azimuthal wave number. The phase wave front recorded in the field of view of beam 0, located to the west, is ahead of the wave front in beam 1, i.e. the wave was eastward.

Since different oscillations often occurred at the same time, in some cases, for example, on October 19, 2014, the eastward oscillation harmonics were observed simultaneously with the westward ones.

For example, Figure 3, *a* shows oscillations observed on October 19, 2014; the wave filtered in the 1.25–4 MHz range (Figure 3, *b*) is westward. It is possible to identify the eastward oscillation component with a frequency of ~6 MHz observed between 2.7 and 2.9 UT (Figure 3, *c*).

To determine the polarization of the waves under study, besides the difference between oscillation phases obtained in one latitude range along adjacent beams, we examined a phase front shift along one beam for a number of events. Since, as mentioned above, beams with high time resolution are directed approximately along the magnetic meridian, the determination of the phase difference at different latitudes along one beam provides insight into the wave structure across L shells and allows us to estimate the radial wave number:

$$k_r = \frac{2\pi\Delta\varphi_x}{\Delta L}, \tag{6}$$

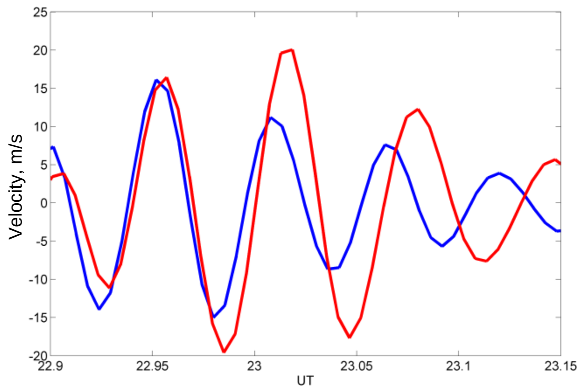

Figure 2. Oscillations filtered in the 4–7 MHz range, recorded in the field of view of beams 0 (blue line) and 1 (red line) on September 4, 2014

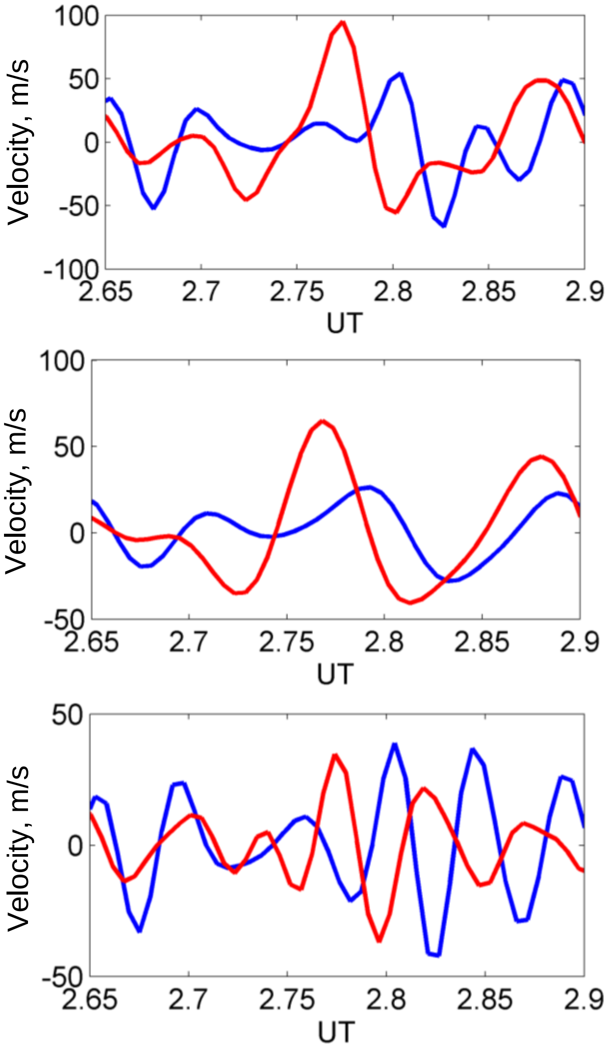

Figure 3. Oscillations recorded in the field of view of beams 1 (blue line) and 2 (red line) on October 19, 2014: oscillations filtered in the 1.25–4 MHz range; a westward wave (m<0) with a frequency of ~2.5 MHz (*a*); the same oscillations filtered in the 4–8 MHz range (*b*); eastward oscillations (m>0) with a frequency of ~6 MHz (*c*)

where $\Delta\varphi_x$ is the wave phase difference along one beam at different geomagnetic latitudes φ_1, φ_2, to which correspond the magnetic shells L_1 and L_2, and

$$\Delta L = L_2 - L_1, \tag{7}$$

where L_1 and L_2 are found by the IGRF model.

The value of k_r was determined for the events of April 18, September 17, October 19, 2014, and March 14, 2015. For other cases, the limited time resolution (about 18 s) and the minor phase difference $\Delta\varphi_x$ made it impossible to estimate this value. For the same reasons, the errors in determining the phase difference and k_r are great (20–40 %); calculations, however, provide some insight into the $\Delta\varphi_x$ and k_r values. The calculation results together with the m values are shown in Table 2. The azimuthal wave number was found from the formula

$$k_a = \frac{m}{L}. \tag{8}$$

For the March 14, 2015 event, we present data on the oscillations recorded between 19:50 and 20:10 UT. For the October 19, 2014 event, we give two k_r values because at

Table 2

Date	φ_1	φ_2	L_1	L_2	k_r	k_a	m
April 18, 2014	59.3	60.9	3.89	4.29	1.4	4.3	22
September 17, 2014	58.9	60.2	3.80	4.09	0.9	1	5
October 19, 2014	62.9	63.4	4.99	5.13	3.9–0.2	2.6	17
March 14, 2015	64.9	66.1	5.67	6.20	1	0.8	6

02:51 UT the wave changed its propagation direction from equator – pole to pole – equator, the radial component of the wave vector decreasing by an order of magnitude. In other cases, the wave was poleward. In the two cases shown in Table, the wave polarization in the plane perpendicular to field lines is mixed with both waves had m<10. In another case, the poloidal component of oscillations prevails (k_a>k_r). The wave recorded on October 19, 2014 first had mixed polarization with k_r>k_a, but after changing its direction it changed the polarization into poloidal (a similar polarization change is described in [Zolotukhina et al., 2008]). In this case, the azimuthal wave number did not change significantly in modulus, i.e. in the azimuthal direction the wave changed its direction from east to west.

In all but one cases (October 19, 2014), waves were recorded under quiet magnetospheric conditions, where the planetary index K_p varied from 2+ to 3+. The solar wind particle density did not exceed an average of 5–10 cm^{-3}. Values of the auroral index *AE* ranged from 100 to 600 nT. The observed oscillations were detected when the interplanetary magnetic field (IMF) was southward. On October 19, 2014, the oscillations began during a weak magnetic storm when the *SYM-H* index was minimum, –35 nT, against a sharp increase in the SW density up to 11 cm^{-3} for northward IMF. The *AE* index was ~500 nT.

DISCUSSION

Waves with small values of the azimuthal wave number enter the magnetosphere from outside [Leonovich et al., 2015; Mazur, Chuiko, 2017]. In this case, field line eigenoscillations are triggered by fast magnetoacoustic waves penetrating from interplanetary space directly or emerging at the magnetopause due to instability, caused by the influence of incoming solar wind streams. Oscillations with small m generally have toroidal polarization.

According to radar observations, waves with small m are mostly poleward [Yeoman et al., 2012]. This feature can be explained by the theory of field line resonance [Walker et al., 1979]. Since the Alfvén velocity outside the plasmapause, on average, decreases with latitude, the field line resonance frequency also decreases. This causes the phase front to move poleward. As shown in Table 2, to small m corresponds poleward wave propagation, which is consistent with other observations and the theory.

Waves with large azimuthal wave numbers are considered to be driven by intermagnetospheric processes. Drift or drift bounce instabilities are often discusses which develop when energetic particles, involved in the resonant interaction with poloidal field line eigenoscillations, penetrate into the magnetosphere during substorms [Glassmeier et al., 1999]. In addition, they can be driven by alternating currents, associated with the movement of clouds of charged particles in the magnetosphere [Mager, Klimushkin, 2007; Zolotukhina et al., 2008].

As derived from radar observations, waves with large m tend to propagate equatorward [Tian et al., 1991; Yeoman et al., 1992, 2000]. For the proton–wave interaction Mager et al. [2009] have proposed an explanation relating the phase shift of the wave front to the dependence of the velocity of charged particles moving in the azimuthal direction on the distance to Earth. Since on distant L shells the drift velocity is higher, the cloud of charged particles is extended in the equatorial plane in the form of a spiral, thus causing waves to move to Earth or, in the case of footprints of field lines on the surface, to propagate from the pole to the equator. In the October 19, 2014 event, the wave at the beginning of the observation was poleward, but soon became equatorward. This feature is consistent with the above theory, but the waves interacting with drifting protons are westward in the azimuthal direction.

However, in the April 18, 2014 event, the small-scale azimuthal phase wave front was equatorward. Such cases relating to waves with intermagnetospheric sources are described in [Mathews et al., 2004; Rae et al., 2014]. Baddeley et al. [2017] also describes oscillations with similar features: the wave propagating from the midnight meridian with close values of m, which had intermagnetospheric origin, was equatorward. It is worth noting that in the case we discuss the wave has poloidal polarization, while Baddeley et al. [2017] attribute this wave to the toroidal field line resonance mode.

A major source of energy of magnetospheric pulsations is considered to be ions. Their main part enters the magnetosphere from the tail and drifts to the dusk meridian in Earth's dipole field [Anderson et al., 1990]. Takahashi et al. [1987] have assumed that eastward waves can interact with protons that under the action of the electric dawn–dusk field are also move to the east. From the viewpoint of a stationary observer, the wave propagated to the east, the proton drift velocity should have been higher than the phase velocity of the wave. In addition to the interaction with protons, waves may experience an enhancement in the resonant interaction with energetic electrons drifting to the east in Earth's dipole field. Hori et al. [2018] have described an observation of waves caused by a substorm and azimuthally propagating in both directions with eastward waves associated with electron fluxes near the equatorial plane of the magnetosphere. A mode subject to this interaction due to the drift instability is the drift-compressional mode [Kostarev, Mager, 2017] whose frequency, as in most cases we consider, is lower than frequencies of Alfvén field line oscillations.

CONCLUSION

We have examined a number of recordings of electromagnetic waves with positive azimuthal wave numbers, i.e. eastward waves. The observations were made with the Ekaterinburg mid-latitude coherent radar in the nightside ionosphere in 2014 and 2015. Some beams of the radar worked at a high time resolution mode. We have used satellite data obtained in the observation sector corresponding to magnetic shells in footprints of which the radar received the signal. The analysis of the events has shown the following.

- In some events of 2014 and 2015, among the Pc5 oscillations observed with the radar, which are related to reflections from the ionosphere, ~13 % of waves have $m>0$ with some of them observed simultaneously with other oscillations.
- For four cases of observation of waves with positive m, we have estimated the wavelength in the radial direction k_r and polarization. Oscillations with small m feature mixed polarization (two cases); and those with large m, polarization with a dominant poloidal component. In cases with small m, waves in the meridional direction were poleward ($k_r>0$), which is consistent with the concept of the Alfvén field line resonance. In the third case characterized by an intermediate m, the wave also propagated poleward, but then reversed. This also fits the conception of the behavior of field line eigenoscillations. In another case of observation of a wave with a large azimuthal wave number, the wave was poleward, which is atypical for cases with large m [Tian et al., 1991; Yeoman et al., 2000, 2012].

Furthermore, as derived from the results obtained by Chelpanov et al. [2018], in most cases including those described in the previous section, the frequency of oscillations observed with the radar is much lower than the frequencies of field line eigenoscillations in footprints of which we detected radar signal reflections. The frequency of field line eigenoscillations was estimated from data on magnetic field strength and particle density in the magnetosphere, acquired from satellites crossing the sector of radar observations.

These waves with frequencies lower than those of the Alfvén resonance might be related to the drift-compressional mode [Kostarev, Mager, 2017; Chelpanov et al., 2016]. To confirm this hypothesis requires additional analysis of satellite data on energetic particles and further development of the theory of drift-compressional modes in the magnetosphere.

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