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# POLARIZATION DISTRIBUTION OF TRANSVERSE ULF WAVES ACCORDING TO VAN ALLEN PROBE A DATA: WHETHER TOROIDAL AND POLOIDAL WAVES EXIST SEPARATELY IN THE MAGNETOSPHERE?

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**Abstract.** Ultralow-frequency (ULF) waves play an important role in energy transfer within Earth's magnetosphere due to intensive interaction with the surrounding plasma. Previous works have assumed that these waves are strictly divided by polarization into toroidal, when the magnetic field oscillates in the azimuthal direction, and poloidal, when it oscillates in the radial direction. The former are azimuthally large-scale and are excited by external sources, whereas the latter are small-scale and are generated by internal plasma instabilities. Observations show, however, that waves of mixed polarization often occur, and the nature of this mixing has not been explained. In this paper, we carry out a statistical study and show that the polarization of transverse waves has a normal distribution, and the maximum corresponds to oscillations of the toroidal and poloidal components with the same amplitude. At the same time, the spatial distributions of toroidal and poloidal waves are clearly different, but only lead to a small shift in the position of the distribution maximum. This result suggests that in order to compare the theory with ULF wave observations it is necessary to take into account the processes of polarization change, which can affect wave-particle interactions in the magnetosphere.

**Keywords:** magnetosphere, ULF waves, Alfvén waves, polarization.

## INTRODUCTION

Alfvén waves in the magnetosphere are eigenoscillations of geomagnetic field lines. These waves fall within the long-period part of the ultralow-frequency (ULF) range i.e. their wavelength is comparable to the size of Earth, which is why they play a key role in energy transfer through the entire magnetosphere [Guglielmi, Troitskaya, 1973]. They can generate electric fields parallel to the magnetic field, which play a major role in electron acceleration that cause auroras [Kostarev et al., 2021]. ULF waves are assumed to be vital to the quasi-viscous transfer of energy and momentum to the magnetosphere from the solar wind [Leonovich, Mishin, 1999] and to the acceleration of polar wind particles [Guglielmi, Lundin, 2001]. Plasma instabilities associated with ULF waves can play a significant part in substorm initiation [Samson et al., 1992; Antonova et al., 2009; Golovchanskaya et al., 2018].

Alfvén waves in the magnetosphere are generated through a variety of mechanisms, both external (with respect to the magnetosphere) and internal. External mechanisms relate mainly to waves having a small azimuthal wave number ($m$~1). These mechanisms are somehow linked to the interaction of the magnetosphere with the solar wind: solar wind ram pressure pulses, hydromagnetic instabilities at the boundary of the magnetosphere, direct transition of waves from the solar wind to the magnetosphere [Agapitov, Cheremnykh, 2013]. Azimuthally large-scale waves should have toroidal polarization when field lines oscillate in the azimuthal direction (Figure 1, left). In this case, the electric field vector oscillates in the radial direction.

Intramagnetospheric mechanisms of ULF wave generation are related to waves with large azimuthal wave numbers ($m \gg 1$). These mechanisms include various plasma instabilities [Chen, Hasegawa, 1991], alternating currents inside the magnetosphere and/or the ionosphere [Mager, Klimushkin, 2007]. Azimuthally small-scale waves are characterized by field-line oscillations in the radial direction (see Figure 1, right). In this case, the electric field vector oscillates in the azimuthal direction. Such Alfvén waves are called poloidal. Note that poloidal Alfvén waves should transform into toroidal ones. For impulse-excited waves, the transformation occurs in time, i.e. at first a wave has poloidal polarization that after some time is replaced by the toroidal one [Mann, Wright, 1995; Leonovich, Mazur, 1998]. For monochromatic waves, the transformation takes place in space, i.e. in one part of its localization region, the wave has poloidal polarization; in another part, toroidal; and gradually moves from the poloidal region to the toroidal one [Leonovich, Mazur, 1993; Klimushkin et al., 1995].

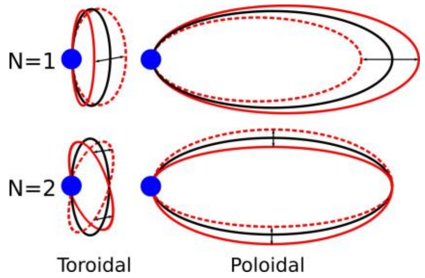


*Figure 1*. Field-line oscillations in toroidal and poloidal Alfvén waves [Klimushkin et al., 2021]. The fundamental (top) and second (bottom) harmonics

The presence of the two wave types differing both in generation mechanisms and polarization raises the question of how clearly these two groups are expressed in their observable manifestations: toroidal and poloidal waves do exist separately, or there is a smooth transition between them. To answer this question, we should use satellite data since waves with $m \gg 1$ do not reach the Earth surface due to the screening effect of the atmosphere [Hughes, Southwood, 1976]. In this paper, we address this question, using data from the Van Allen Probe A satellite.

## 1. DATA

We have used Van Allen Probe A data from January 2017 to October 2018 [Mauk et al., 2013]. During that period, the satellite made one full observation of the magnetosphere. We utilize only 4 s magnetic field vector measurements by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) for the analysis [Kletzing et al., 2013]. The satellite's orbit passes near the magnetic equator (magnetic latitude <20°); therefore, to describe the satellite's position in projection to the equator, we use the McIlwain parameter $L$ [McIlwain, 1961] and local magnetic time (MLT). Van Allen Probe A is no more than 6 $R_E$ away from Earth, which makes it possible to exclude the magnetopause crossing in the time period under study. This configuration of the satellite's orbit is convenient for studying transverse ULF waves, which are usually identified with Alfvén waves. We examine ULF waves at distances $L$>4 since the satellite velocity increases near the perigee of the orbit, thereby causing distortions in ULF wave observations.

ULF waves in the Pc4 and Pc5 ranges, covering wave periods from 45 to 600 s, are convenient to study using a field-aligned coordinate system. Direction along field lines is determined through 10-min moving average, which makes it possible to identify longitudinal disturbances of the magnetic field $b_\parallel$. Magnetic field disturbances across field lines are oriented radially from Earth $b_r$ and azimuthally to the east $b_a$. The choice of the 10-min window is sufficient since Van Allen Probe A does not rise above $L$=6.5, and, according to earlier observations and model calculations at such distances, the frequency of Alfvén waves remains above 5 mHz (200 s period) [Takahashi et al., 2002].

Waves for statistical analysis were selected by searching for individual events. Pc4 and Pc5 disturbances were preliminary extracted from magnetic field measurements, using a bandpass filter. The time period under study was divided into 15-min intervals with a step of 5 min, which ensured sufficient accuracy in determining the start and end time of wave observation. For each magnetic field component and each 15-min interval, a fast Fourier transform was used to construct a frequency spectrum in which a signal at the frequency of a single peak was considered a wave if the peak's width at half maximum was less than 40 % of the peak's frequency. If the peaks were detected in consecutive intervals and their frequencies differed by no more than 2 mHz, this case was considered a single event. Thus, each wave is characterized by the start and end time of its observation, frequency, and average amplitude in each of the three components. The wave amplitude was found after filtering in the ±1 mHz band from the peak's frequency. Wave polarization was defined as the ratio between these average amplitudes: if $\langle b_r \rangle$ is the highest, such a wave is considered poloidal; if $\langle b_a \rangle$, toroidal; if $\langle b_\parallel \rangle$, compression. Further in the paper, we deal only with transverse waves when either $\langle b_a \rangle > \langle b_\parallel \rangle$, or $\langle b_r \rangle > \langle b_\parallel \rangle$.

## 2. RESULTS

Distribution of the satellite dwelling time over MLT sectors is almost uniform and has a maximum in the range $L$=5.5–6.0 (Figure 2, *a*). This maximum is determined by the apogee of the satellite's orbit; however, due to inclination of the orbit, it may shift to higher $L$-shells.

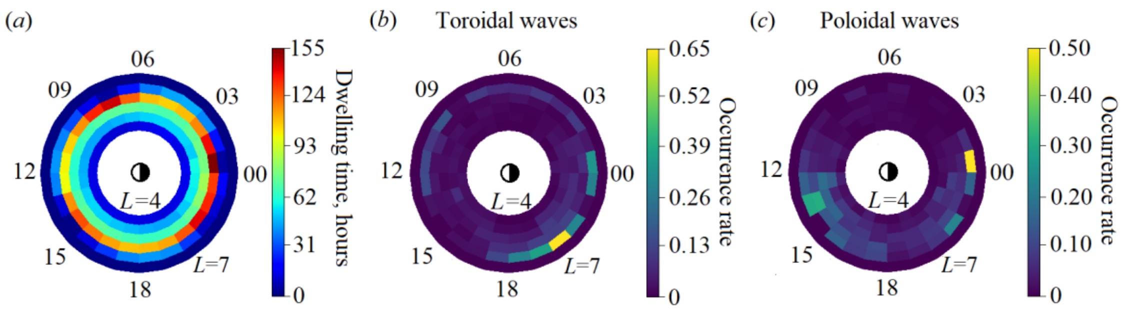


*Figure 2*. Dwelling time of Van Allen Probe A in the outer magnetosphere from January 1, 2017 to October 31, 2018 (*a*). Occurrence rate of toroidal (*b*) and poloidal (*c*) waves. Results projected onto the equatorial plane $L$ — MLT, cell size is 0.5 $R_E$×1 hr ($L$>4)

Figure 2, *b*, *c* clearly shows that spatial distributions of poloidal and toroidal waves differ. Toroidal waves are concentrated in dusk and pre-noon sectors on large *L*-shells, whereas poloidal waves were mainly observed along the ion drift path from midnight to noon, through the dusk sector with maxima near noon and midnight. The obtained distributions of the occurrence rates of toroidal and poloidal waves have both similarities and differences from statistical studies of Pc4 and Pc5 waves based on data from other spacecraft [Anderson, 1993; Liu et al., 2009]. The result presented in Figure 2, *c* corresponds to the distribution of poloidal Pc4 according to Van Allen Probes data collected during one full observation of the magnetosphere from October 2012 to July 2014 [Dai et al., 2015].

Figure 3 illustrates the distribution of values of the $\langle b_a \rangle$-to-$\langle b_r \rangle$ ratio on the log scale, which turned out to be close to the normal distribution with an average value of ~1. This result suggests that most of the observed transverse waves have mixed polarization, and $\langle b_a \rangle \approx \langle b_r \rangle$.

Nonetheless, the average value $\langle b_a \rangle / \langle b_r \rangle$ changes if the waves are grouped according to MLT sectors. Figure 4 shows distributions in four MLT sectors: noon (MLT=09–15 hr), dawn (MLT=03–09 hr), dusk (MLT=15–21 hr),

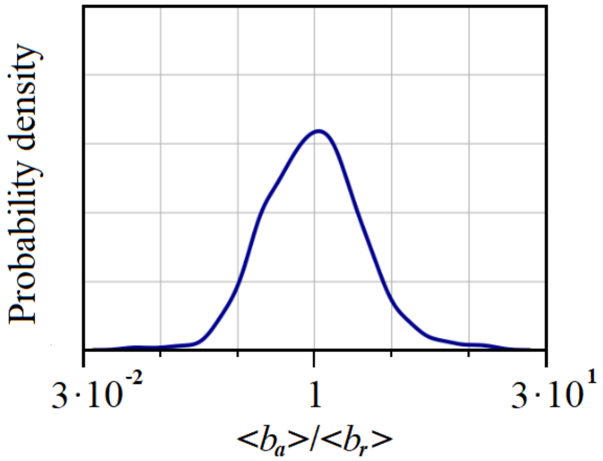


*Figure 3*. Distribution of the ratio of average oscillation amplitudes in the azimuthal and radial magnetic field components $\langle b_a \rangle / \langle b_r \rangle$ for transverse waves

and night (MLT=21–03 hr). There are more poloidal waves in the noon sector, and toroidal waves in the night sector. The distribution parameters in the dawn and dusk sectors are intermediate between noon and night.

## 3. DISCUSSION

Even in the first studies on the Alfvén-wave theory, waves were classified into azimuthally large-scale toroidal and azimuthally small-scale poloidal [Radoski, 1967; Cummings et al., 1969]. Toroidal waves were associated with external generation sources; and poloidal, with internal ones [Chen, Hasegawa, 1991]. In a statistical study [Anderson, 1993], observed ULF waves

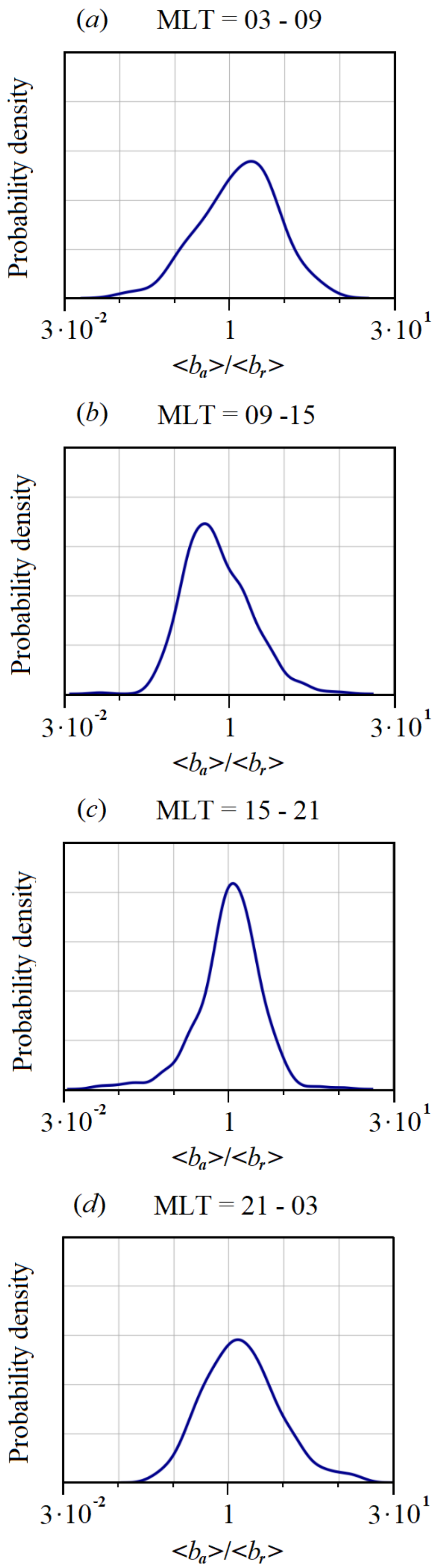


*Figure 4*. Distributions $\langle b_a \rangle / \langle b_r \rangle$ for transverse waves in the dawn (*a*), noon (*b*), dusk (*c*), and night (*d*) sectors of the magnetosphere

with periods from 10 s to 10 min were divided into five types: Pc4 poloidal waves, fundamental modes of Pc5 toroidal waves, high harmonics of toroidal waves, Pc5 compression waves, and incoherent noise. Liu et al. [2009] examined separately toroidal and poloidal waves in the Pc4 and Pc5 ranges, using THEMIS observations, and highlighted differences in their spatial distribution. In later studies, individual wave types were studied such as Pc4 poloidal waves [Dai et al., 2015] or multi-harmonic toroidal waves [Yamamoto et al., 2022]. There are also many case studies of Alfvén wave observation, which, despite the presence of oscillations simultaneously in several directions, classify the observed waves as toroidal or poloidal, depending on the direction in which the amplitude is maximum (e.g., [Dai et al., 2013; Korotova et al., 2016; Le et al., 2021]).

The possibility that an Alfvén wave can change polarization has been explored [Radoski, 1974; Leonovich, Mazur, 1993, 1998; Mann, Wright, 1995], but little attention was paid to it during observation analysis. We know only a few studies describing the observation of polarization change by satellites [Zolotukhina et al., 2008; Sarris et al., 2009; Leonovich et al., 2015; Wei et al., 2019; Takahashi et al., 2018]. From the distributions shown in Figures 3 and 4 we can see that there is no rigid division into toroidal and poloidal waves. Statistics shows that transverse waves usually have mixed polarization and often $\langle b_a \rangle \approx \langle b_r \rangle$. A similar result, but based on less statistics, was obtained in [Agapitov, Cheremnykh, 2011], yet it was not formulated explicitly there. Rubtsov et al. [2023a, b] have obtained similar distributions from Arase data. We assume that this is a consequence of observing the process when Alfvén waves change polarization at different stages. Extensive statistics of observations just gives the maximum probability density for the case corresponding to the middle of the change, i.e. $\langle b_a \rangle \approx \langle b_r \rangle$.

Moreover, it is surprising that poloidal waves dominate on the dayside where there are seemingly more toroidal waves generated from the outside (Figure 4, *b*). This feature has also been found in some statistical studies [Chi, Le, 2015]. It may be related to the existence of long-lasting poloidal waves that can be observed on the dayside during several consecutive orbits of Van Allen Probes [Korotova et al., 2016; Rubtsov et al., 2021]. These waves can be generated at a small radial Alfvén frequency gradient [Choi, Lee, 2021] or be modes of the transverse Alfvén resonator [Leonovich, Mazur, 1990; Vetoulis, Chen, 1994; Klimushkin, 1998]. To answer this question requires further study of such observations.

Note that the statistical results we have presented may have inaccuracies, including those related to the method of determining wave polarization. In this work, we have analyzed average oscillation amplitudes in all magnetic field components over the period of wave observation. However, transverse waves of odd harmonics have a node near the magnetic equator, which can lead to underestimation of their average amplitudes. At the same time, poloidal Alfvén waves at finite plasma pressure have a field-aligned component that has an antinode at the equator [Klimushkin et al., 2004]. Taken together, this can result in classification of odd harmonics of transverse waves as compression waves and they will not be included in the current statistics. Poloidal waves have the most noticeable compression component [Klimushkin et al., 2004], so we can assume that their number is underestimated in this work.

## CONCLUSION

From the results of Van Allen Probe A observations we have found that there are no individual maxima corresponding to purely toroidal and purely poloidal waves in the polarization distribution of transverse ULF waves. The polarization distribution of waves is normal, and its maximum pertains to the approximate equality of average oscillation amplitudes of the azimuthal $\langle b_a \rangle$ and radial $\langle b_r \rangle$ magnetic field components. At the same time, the maximum distribution shifts in different MLT sectors: at the dayside — to the poloidal region, and at night — to the toroidal one.

The data obtained makes us to reconsider the generally accepted approach to Alfvén waves from the conceptual point of view, when poloidal and toroidal waves were considered separately. The noticeable asymmetry in space indicates that the factors determining one or another wave polarization are constant. In the future, it is important to determine what caused the result $\langle b_a \rangle \approx \langle b_r \rangle$: the development of a wave or the operation of different mechanisms of wave excitation in the same spatial region. In the former case, it is necessary to find out the spatial and temporal scales of the polarization change. In the latter case, questions arise as to which mechanism is responsible for generating a specific polarization (toroidal and poloidal) and whether these mechanisms can act simultaneously or sequentially, which yields the statistical result. $\langle b_a \rangle \approx \langle b_r \rangle$. Finally, it is important to figure out how Alfvén waves interact with charged particles inside the magnetosphere in both the former and latter cases.

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