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# ROLE OF ULF WAVE ACTIVITY IN SOLAR WIND-MAGNETOSPHERE INTERACTIONS AND MAGNETOSPHERIC ELECTRONS ACCELERATION

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## Abstract

The solar wind-magnetosphere interaction has a turbulent character, which is not accounted for by commonly used geomagnetic indices and OMNI parameters. To quantify the level of low-frequency turbulence/variability of the geomagnetic field, IMF, and solar wind plasma, we have introduced ULF wave power indices. These simple hourly indices are based on the integrated spectral power in the band 2-7 mHz.

The application of the interplanetary index to the analysis of conditions in the solar wind before magnetic storm onsets has shown that a weak irregular increase of the solar wind density is observed on average 2 days prior to storm commencement. The enhancements of relativistic electrons at the geosynchronous orbit are known not to be directly related to the intensity of magnetic storms. We found that the electron dynamics correlated well with intervals of elevated ground ULF wave index. This fact confirmed the importance of magnetospheric ULF turbulence in energizing electrons up to the relativistic energies.

## Introduction

The interaction between the solar wind (SW) and terrestrial magnetosphere is the primary driver of many processes and phenomena occurring in the magnetosphere. This interaction has often been viewed using the implicit assumption of quasi-steady and laminar plasma flow. However, many of the energy transfer processes in the magnetospheric boundary regions have a sporadic/bursty character, and observations have highlighted the importance of including the effects of turbulence as well [1, 2]. The turbulent character of SW drivers and the existence of natural MHD waveguides and resonators in near-terrestrial space in the lower ULF frequency range (1-10 mHz) ensures a quasi-periodic magnetic field response to forcing at the boundary layers. Therefore, much of the turbulent nature of plasma processes of SW-magnetosphere interactions can be monitored with ground or space observations in the ULF range.

Progress in understanding and monitoring the turbulent processes in space physics is hampered by the lack of convenient tools for their characterization. Various geomagnetic indices (Kp, Dst, AE, PC, etc.) quantify the energy supply in certain regions of the coupled SW-magnetosphere-ionosphere system, and are used as primary tools in statistical studies of solar-terrestrial relationships. However, these indices characterize the steady-state level of the electrodynamics of the near-Earth environment. Till recent there was no index characterizing the turbulent character of the energy transfer from the SW into the upper atmosphere and the short-scale variability of near-Earth electromagnetic processes. A new hourly "turbulence" index, using the spectral ULF power in frequency band 1-2 mHz to 8-10 mHz has been introduced in [3]. The wave power index characterizes the ground ULF wave activity on a global scale and is calculated from world-wide array of high-latitude stations data. The ground power index is augmented by interplanetary and geostationary ULF wave indices, as indicators of the turbulent state of the interplanetary space and magnetosphere.

In this paper we test the significance of these ULF indices for the statistical studies of various aspects of the solar-terrestrial relationships and demonstrate their merits and disadvantages.

## Algorithm of the ULF wave index construction

Algorithm of the ULF wave index [3] relies on the estimate of the ULF wave power $F_j = B^2_j\ (f)$ in the band $\Delta f$ from $f_L$ to $f_H$ averaged over $Nc$ components ($j$=1,2..$Nc$):

$$ULF = \frac{1}{N_C}\left[\Delta f \sum_j \int_{fL}^{fH} F_j\,(f)df\right]^{\frac{1}{2}}$$

The signal component $S$ of the spectral power is calculated similar, but with the background spectral power $F^{(B)}(f)$ subtracted from the total spectral power $F(f)$, namely $F_j(f) \to F_j(f) - F_j^{(B)}(f)$. The background spectrum is determined as a least-square fit of the power-law spectral form $F^{(B)}(f) \propto f^{-\alpha}$ in a chosen frequency band. The spectral power below $F^{(B)}(f)$ is attributed to noise $Nj(f)$, so $T_j = S_j + N_j$.

The final product is composed from the set of hourly ULF wave indices:

- Ground ULF wave index ($T_{GR}$, $S_{GR}$) is a proxy of global ULF activity. For its production, the algorithm selects the peak value of wave powers of 2 horizontal components from all the magnetic stations in the sector from 05 to 15 MLT (to avoid irregular nighttime disturbances), and in the latitudinal range from 60º to 70º geomagnetic latitudes;
- Geostationary ULF wave index ($T_{GEO}$, $S_{GEO}$) is calculated from 1-min 3-component magnetic data from GOES satellites to quantify magnetic fluctuations in the region of geostationary orbit;
- Interplanetary ULF wave index to quantify the short-term IMF variability ($T_{IMF}$, $S_{IMF}$) is calculated from the 1-min data from the interplanetary satellites WIND, ACE.

The histogram of the occurrence probability of log $S_{IMF}$ index is shown in Figure 1.

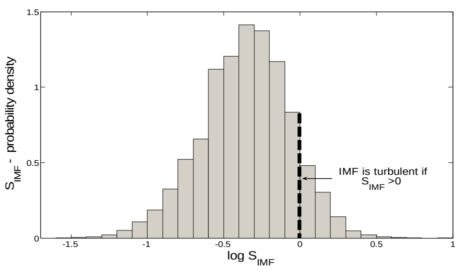


**Figure 1**. The occurrence probability of the log $S_{IMF}$ index. Zero point denotes a chosen boundary between the quiet and turbulent IMF.

The typical value of $S_{IMF}$ is about 1 nT. Further we demonstrate that a wide range of space physics studies benefits from the introduction of the ULF wave index.

## Solar wind/magnetosphere coupling

The turbulent/eddy viscosity of the SW flow passing the magnetosphere is controlled to a considerable extent by the level of upstream turbulence. However, the turbulence of the magnetosheath plasma which directly interacts with the magnetosphere, is significantly different for the conditions of quasi-parallel or quasi-perpendicular bow shock [4].

Nonetheless, the degree of coupling of the SW flow to the magnetosphere appears to be influenced by the level of SW/IMF turbulence upstream of the Earth [2]. The eddy viscosity concept predicts that the coupling to be lessened when the level of upstream turbulence is lessened. The effective Reynolds numbers of the SW and magnetosheath flows and that of the internal magnetospheric flows are very high, so the magnetosphere behaves as a turbulent high-Reynolds-number system.

Therefore, the presence of turbulence inside and outside the magnetosphere should have profound effects on the large-scale dynamics of the system through eddy viscosity and diffusion.

The distribution of $S_{GR}$ and $Bz$ samples (Figure 3, lower panel) is also skewed: for $Bz$<0 the ground wave power is generally higher than for $Bz$>0. Thus, the reconnection and particle injection processes, both controlled by $Bz$, contribute to the generation of the magnetospheric ULF activity.

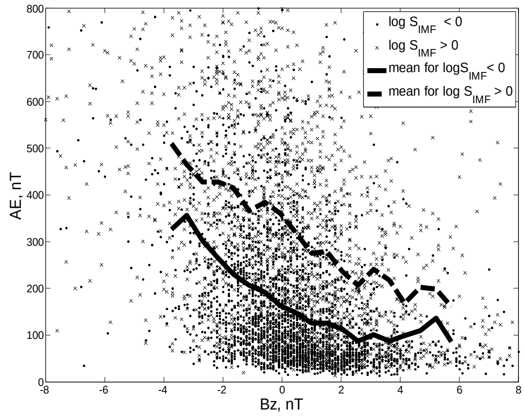


**Figure 2.** The dependence of auroral activity (*AE* index), on the IMF driver (*Bz*) for laminar, log $S_{IMF}$<0, and turbulent, log $S_{IMF}$ >0, IMF.

Using the introduced ULF index IMF, here we verify the fact that when the SW is more turbulent, the effective degree of its coupling to magnetosphere is higher [2].

Auroral response, as characterized by hourly *AE* index, is compared with a strength of the SW driver, determined by the IMF *Bz* component, for the laminar and turbulent IMF for the period 1994-1995 (Figure 2). The IMF is considered noisy when log $S_{IMF}$>0, and IMF is calm when log $S_{IMF}$<0. Comparison of median curves shows that under southward IMF (Bz<0) *AE* nearly linear grows upon increase of the magnitude of *Bz*, whereas the average *AE* response to the turbulent IMF is higher. This difference is most significant for northward IMF, when one expects the viscous interaction to be dominant over the reconnection, but it reveals itself even under weak southward IMF. This comparison confirms that the magnetosphere is driven more weakly when the IMF turbulence level is low.

## Which IMF parameters do control the ground ULF wave activity?

Numerous studies showed that the key parameter that controls ground ULF activity is the SW velocity [6]. The correspondence between the hourly values of ground ULF index $S_{GR}$ and $V$ (Figure 3, upper panel) confirms this result. The correspondence between the ground wave power and $V$ has somewhat different character for slow SW (<450 km/s) and fast SW (>450 km/s). The statistical swarm has a clear cut-off lower boundary and an upper cut-off, similar to the IMF turbulence, indicating that for any $V$ the ground wave activity cannot exceed some saturation level. The occurrence of cut-off lower and upper boundaries (dashed lines) signify that the intensity of ground fluctuations is within certain limits for any $V$. These statistical features should be understood in the frameworks of the theory of ULF wave excitation through the SW shear flow instability.

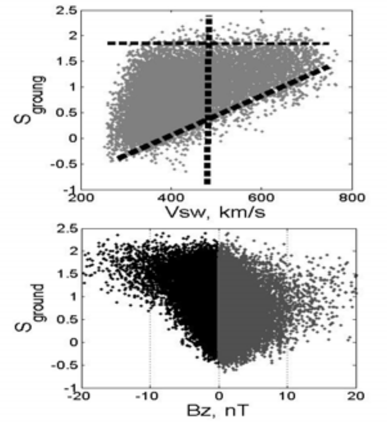


**Figure 3**. Correspondence between the global ground ULF activity, as characterized by log $S_{GR}$, and the SW velocity *V* (upper panel). The lower panel shows the log $S_{GR}$ dependence on IMF *Bz*.

The interplanetary ULF wave power index can be used as a simple and convenient tool for the statistical examination of the SW and IMF turbulence.

## ULF wave index and "killer" electrons

Here we consider application of the ULF wave index to the problem of magnetospheric electron acceleration up to relativistic energies. The relativistic electron events are not merely a curiosity for scientists, but they can have disruptive consequences for spacecrafts [6].

Commonly, relativistic electron enhancements in the outer radiation belt are associated with magnetic storms [7], though the wide variability of the response and the puzzling time delay 2 days between storm main phase and the response has frustrated the identification of responsible mechanisms. Moreover, some electron events may occur even without magnetic storm or during very mild storms ($|Dst| \sim 0$-40 nT). The example of such event on December, 1999 is shown in Figure 4. In this situation a high-speed solar stream occurs without a favorable *Bz*, and consequently without a noticeable storm (as measured by *Dst* index).

The efficiency of these non-identified mechanisms of the energetic electron acceleration is strongly enhanced upon increase of *V*. Because the SW does not interact directly with magnetospheric electrons, some intermediary must more directly provide energy to the electrons. Rather surprisingly, ULF waves in the Pc5 band (few mHz) have emerged as a possible energy reservoir [8]: the presence of Pc5 wave power after minimum Dst was found to be a good indicator of relativistic electron response [9].

Therefore, in a laminar, non-turbulent magnetosphere the "killer" electrons would not appear. Mechanism of the acceleration of ~ 100 keV electrons supplied by substorms is a revival of the idea of the magnetospheric geosynchrotron: pumping of energy into seed electrons is provided by large-scale MHD waves in a resonant way, when the wave period matches the multiple of the electron drift period [10,11].

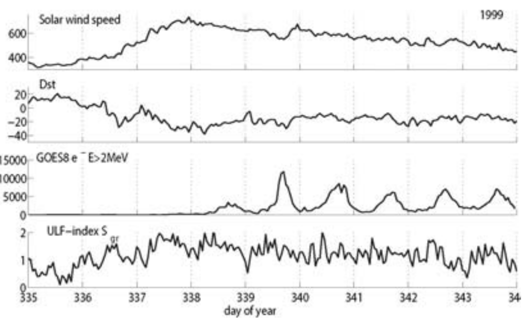


**Figure 4**. The "electron event" without magnetic storm observed at GOES-8 on December, 1999.

However, this mechanism is not the only one, the local resonant acceleration upon interaction with high-frequency chorus emissions was claimed to be responsible for the relativistic electron occurrence [12].

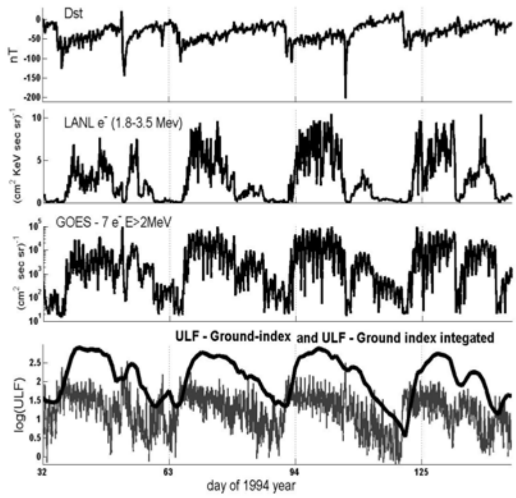


**Figure 5**. Comparison between the *Dst* index, electron fluxes at geostationary orbit measured by LANL and GOES-7 cumulative index $\langle S_{GR}\rangle$ and ULF index $S_{GR}$ during 1994.

The example presented in Figure 5 shows that the increases of the relativistic electron fluxes up to 2-3 orders occur after weak storms, but the increase after strong storm is much shorter and less intense, whereas the correspondence with ULF wave activity is quite well for all events. Moreover, a long-term persistent ULF activity is more important for electron acceleration than short-term ULF bursts though intense. Thus, the cumulative ULF index:

$$\langle S_{GR}(t)\rangle = \int_{-\infty}^{t} S_{GR}(t')\exp\left[-\frac{(t-t')}{\tau}\right]dt'$$

integrated over time pre-history $\tau$ = 2-3 days might be a better parameter than pure ULF index, as illustrates the bottom panel in Figure 6. Indeed, the correlation of electron flux with the integrated ULF index increases substantially, from 0.5 to 0.8 (Figure 6), and even becomes slightly higher than the correlation with the SW velocity.

The cross-correlation function shows that the elevated level of ULF wave activity precedes the peak of relativistic electron flux for about 2 days, whereas the same delay for the cumulative index is about 1 day.

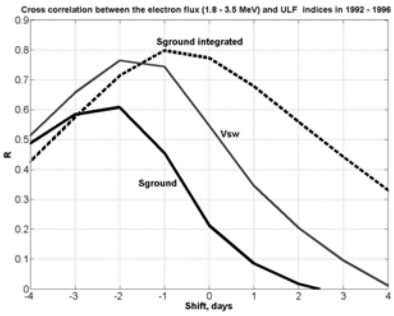


**Figure 6**. The cross-correlation function between the electron flux at geostationary orbit measured by LANL, SW velocity, and cumulative index $\langle S_{GR} \rangle$ (dashed line) and ULF index $S_{GR}$ (solid).

This increase of correlation, probably, implies the occurrence of a cumulative effect of some diffusion process. Thus, the long-lasting ULF wave activity is more important for the electron acceleration than just instant values.

## Conclusions

The new ULF wave power index is a simple and convenient tool for the description of the turbulence of the SW-magnetosphere system and it can be applied to various space physics problems. Application of this index to the statistical examination of the SW plasma structure prior magnetic storms revealed medium-term precursors of severe space weather. The analysis based on the usage of these indices has elucidated the role of ULF turbulence in the magnetosphere response to the SW/IMF forcing.

Using the introduced indices, we have examined statistical relationships between the "killer" electrons and ULF activity. As expected, the correlation between the variations of electrons flux and *V* is high, but at the same time the interconnection between electrons flux and ULF wave power also remains high throughout all phases of solar cycle.

This indicates that the mechanism of "magnetospheric geosynchrotron" (but not the only one!) contributes to the electron acceleration.

Therefore, the ULF index should be taken into account by any adequate space radiation model. The ULF index database since 1991 up to nowadays is freely available via anonymous FTP server (space.augsburg.edu/MACCS/ULF-index) for all interested researchers for further validation and statistical studies.

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