A New ULF Wave Index and its Comparison with Dynamics of Geostationary Relativistic Electrons

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Abstract. A new ULF wave index, characterizing the turbulent level of the geomagnetic field, has been calculated and applied for the analysis of relativistic electron enhancements during space weather events in April-May 1994 and September 1999. This global wave index has been produced from the INTERMAGNET, MACCS and CPMN dense arrays of ULF magnetometers in the Northern hemisphere. A similar ULF wave index has been calculated using magnetometer data from geostationary (GOES) and interplanetary (Wind, ACE) satellites. During the analyzed periods several magnetic storms occurred, and several significant increases of relativistic electron flux up to 2-3 orders of magnitude were detected by geostationary monitors. However, these electron enhancements were not directly related to the intensity of magnetic storms. Instead, and rather unexpectedly, they correlated well with intervals of elevated ULF wave index, caused by the occurrence of intense Pc5 pulsations in the magnetosphere. This comparison is an additional indication of the possible importance of magnetospheric ULF turbulence in energizing relativistic electrons. The ULF-index database is freely available via FTP for all interested researchers for further validation and statistical studies.

1. Introduction: the Necessity of a New ULF Wave Index

The interaction between the solar wind and Earth’s magnetosphere is the primary driver of many of the processes and phenomena occurring in the magnetosphere and ionosphere. This interaction has often been viewed with considerable success using the implicit assumption of quasi-steady and/or laminar plasma flow. However, new conceptions of the magnetospheric plasma dynamics are being developed, in which turbulence plays a fundamental role [Antonova, 2000; Borovsky et al., 2003]. Progress in understanding and monitoring these turbulent processes in space physics is hampered by the lack of convenient tools for their characterization.

Various geomagnetic indices (Kp, AE, Dst, ASYM, PC) and averaged solar wind/IMF parameters quantify the energy supply in certain regions of the solar wind-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. The turbulent character of solar wind drivers and the existence of natural MHD waveguides and resonators in the magnetospheric plasma in the 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 solar wind-magnetosphere-ionosphere interactions can be monitored with ground-based or space
observations in the ULF frequency range. In this paper we present a new index, coined a “ULF wave index,” characterizing the turbulent character of the energy transfer from the solar wind into the upper atmosphere and the short-scale variability of near-Earth electromagnetic processes. We suppose that a wide range of space physics studies will benefit from the introduction this new index. Some of them are listed below.

1). The level of upstream turbulence in the solar wind determines the turbulent viscosity of the solar wind flow passing the magnetosphere, and as a result, the degree of coupling of the solar wind flow to the magnetosphere appears to be influenced by the level of turbulence upstream of the Earth. There are indications that the magnetosphere indeed is driven more weakly, especially for northward IMF, when the level of solar wind turbulence is low [Borovsky and Funsten, 2003; Goncharova and Pilipenko, 2004]. Thus, the magnetosphere behaves as a turbulent high-Reynolds-number system, and the presence of turbulence in the flows inside and outside the magnetosphere should have profound effects on its large-scale dynamics through eddy viscosity and diffusion. A long-term time series of wave indices, characterizing the level of IMF and geomagnetic field turbulence, would be a useful database for the development and statistical verification of this high-Reynolds-number phenomenology of the magnetosphere.

2). The variability of solar wind and magnetospheric conditions might be an important factor in triggering magnetospheric substorms [Kamide, 2001]. For example, Tsurutani et al., [1995] showed that large-amplitude Alfvén waves within the body of corotating solar wind streams can support a long period of enhanced AE activity after magnetic storms. Although there is a modest amount of theoretical and observational evidence supporting this view, this idea has not been thoroughly examined by the space community so far, and it is not used for space weather purposes. Enhanced reconnection and viscous interaction in dayside boundary regions, leading eventually to substorms, most probably are accompanied by an enhanced level of turbulence. Therefore, substorm break-ups may be preceded by an increased level of ULF power in the region of the dayside boundary layers [Pilipenko et al., 1998; Solovyev et al., 1999]. Also, the pre-heating of the nightside plasmasheet plasma owing to the resonant absorption of MHD turbulence may provide necessary conditions for the onset of an explosive instability, resulting in a substorm break-up (the so called “thermal catastrophe” model of Goertz and Smith [1989]). Samson et al. [1992] identified a number of intervals in which auroral intensifications occurred during times when nighttime field line resonances occurred, indicating that ULF waves may play a role in triggering substorm intensifications. A statistical study of low-frequency magnetic activity in the night side region of the poleward auroral boundary revealed an enhancement of ULF power about 2-3 hours before the explosive phase of substorms [Yagova et al., 2000]. Further application of reliable statistical methods for the search for wave precursors of substorms will also benefit from the development of a database containing an index quantifying ULF activity.

3). There are currently two contrasting views on the ring current formation during magnetic storms. The conventional idea is that the ring current results from the accumulation of particles injected during substorms. Another view asserts that ring current development results from a sustained enhancement of the convection electric field driven by the IMF/solar wind. A large body of work has demonstrated that it is the solar wind that injects
the particles that create the ring current. In this view it is implicitly assumed that there must be some secondary process that scatters particles from open to closed drift paths. The process must be relatively efficient and continuous, otherwise the injection rate would not depend so strongly on the solar wind electric field. McPherron [1997] suggested that this process is a combination of inherent fluctuations in the solar wind electric fields, waves in the magnetosphere, and inductive electric fields caused by a substorm expansion phase. This process, though being of key importance, is not observable in any existing indices. The necessity to augment the set of existing indices with a proper wave index is evident.

4). Besides magnetospheric problems, ionospheric studies may also benefit from the introduction of a new ULF wave index. Variations of the ionospheric high latitude electric field may substantially exceed the mean value [Crowley and Hackert, 2001], therefore the actual Joule heating would be larger that estimated from the mean time-averaged ionospheric electric field and conductivity. Thus, variability of the electric field should be introduced into climatological models of ionospheric electrodynamics. The easiest way to quantify the variability of the ionospheric electric field is to measure the variability of magnetic variations on the ground, to be expressed in the form of a wave index.

5). Although the proposed ULF wave index is more suited for solar-terrestrial studies, its introduction might be of significant help to the community developing electromagnetic methods of earthquake prediction. Recent studies have revealed that anomalous ULF noise may occur a few days before strong earthquakes [ Fraser-Smith et al., 1990; Pilipenko et al., 1999], caused by the crust micro-fracturing at the final stage of the seismic process [Surkov and Pilipenko, 1999]. Validation of this effect on a large statistical basis with the use of magnetic stations in seismo-active regions will be possible only with the use of a proper ULF wave index. This index will provide the seismic community with an effective tool to distinguish local electromagnetic anomalies from global enhancements of ULF wave activity.

In this paper we concentrate on another problem, which is of primary importance for space weather studies, and where the new ULF wave index is vitally necessary.

1.1. Magnetosphere turbulence and the diffusion/energization of relativistic electrons

The appearance at geosynchronous orbit of relativistic electrons following some geomagnetic storms resists definitive explanation in spite of many years of study. These electron events are not merely a curiosity for scientists, but they can have disruptive consequences for geosynchronous spacecraft [Wilkinson, 1991]. While it has been known that there is a general association between geomagnetic storms and electron enhancements at geosynchronous orbit [Reeves, 1998], the wide variability of the observed response and the puzzling time delay (~1-2 days) between storm main phase and the peak of the response has frustrated the identification of responsible mechanisms and controlling parameters. Ultimately, the solar wind is the energy resource for geomagnetic storms in general and acceleration of electrons to relativistic energies in particular. However, since the solar wind does not directly contact the electrons in question, some magnetospheric intermediary must more directly provide the energy to the electrons. ULF waves in
the Pc5 band have emerged as a possible energy reservoir [Rostoker et al., 1998]. The acceleration mechanisms require seed electrons of a few hundred keV which are usually supplied by substorms and subsequently energized by Pc5 waves.

The observations of Kanekal et al. [1999], Li et al. [1999], and McAdams and Reeves [2001] showed that the enhancements in electron energies (beyond levels expected from conserving adiabatic invariants) at geosynchronous orbit occur rapidly at the onset of a magnetic storm, often within a few hours, but that there is also a slower additional acceleration, varying from storm to storm, so that peak fluxes are often seen only after a number of days. These and other observations of relativistic electron response to magnetic storms showed an inadequacy of the traditional radial diffusion-based energization mechanism and indicated the occurrence of some local acceleration process. This led to proposals for a more efficient energization mechanism based on resonant interaction of drifting electrons with coherent MHD oscillations in the Pc 5 frequency range [Elkington et al., 1999; Liu et al., 1999; Hudson et al., 2000; Summers and Ma, 2000]. This drift-resonance mechanism is in fact a revival of the old idea of a “geosynchrotron” (see references in [Pokhotelov et al., 1999]).

There have been many observations that favor the idea of ULF wave-related acceleration of magnetospheric electrons. In a study of the May 1997 storm by Baker et al. [1998] the wave power in the nominal Pc5 band at one of the CANOPUS stations rapidly increased less than an hour before the appearance of relativistic electrons, prompting the authors to suggest that Pc5 pulsations were an acceleration mechanism for these electrons. The use of one station only is evidently insufficient for the construction of ULF wave index, because this index would suffer from unresolved mixtures of spatial (owing to inevitable station rotation) and temporal variations.

There is better observational support for a ULF contribution to the later, slower energization of electrons. In a comprehensive study, O'Brien et al. [2001] performed a superposed epoch analysis to compare storms with and without the appearance of relativistic electrons, using hourly noon-reconstructed electron fluxes (>2 MeV) from GOES and LANL geosynchronous monitors. They showed that long duration elevated Pc5 ULF wave power during the recovery phase appeared to discriminate better than Dst or AE between those storms that do and do not produce relativistic electrons. Mathie and Mann [2001] showed that electron events had higher ULF power at the mid-latitude SAMNET stations by about an order of magnitude in the recovery phase. Main phase intensity, regardless of how it was measured, did not appear to be an important indicator of subsequent electron behavior.

O'Brien et al. [2001] used a wave power (further named for brevity as B-index) calculated from Fourier spectra in a 2-hour sliding window from 11 selected INTERMAGNET stations with L between 3.5 and 7.0. Powers from all magnetic vector components were summed up in the 150-600 s band, and a station with the highest power was chosen. However, the B-index wave index needs to be further elaborated to avoid the following drawbacks: a) Usage of the vertical Z component, which is very sensitive to local geoelectric inhomogeneities and cannot be a good indicator of magnetospheric ULF activity; b) the limited number of with large uneven spatial gaps between them; c) any LT was considered, so the B-index is strongly influenced by irregular nightside substorm activity.
Moreover, the usage of a wave index based on band-integrated wave power only may be insufficient, because this type of index cannot discriminate between irregular wide-band variations and narrow-band waves. For example, Posch et al. [2001] applied to the analysis of ULF dynamics during GEM storms a simple measure of the fraction of narrow-band pulsations in observed wave power – the pulsation index introduced by Glassmeier [1995]. This index is calculated as the ratio \( R_G \) between the wave power in a narrow band (2-10 mHz) and wide band (0.2-10 mHz). The ULF activity during the main phase, when rapid acceleration of electrons occurred, was in fact broad-band (\( R_G \) is low). This broad-band wave activity is caused by other mechanisms than typical Pc5 pulsations, and their features (spectrum, transverse spatial scale) do not match the current theories of the electron acceleration by ULF waves [Pilipenko et al., 2001]. At the same time, the ULF activity in the recovery phase was narrow-band in the dawn-to-noon LT sector (\( R_G \) is high). These pulsations thus might be related to the gradual slow increase of relativistic electron fluxes owing to drift-resonance acceleration.

A convincing statistical evaluation of possible coupling between ULF activity and relativistic electron dynamics demands a quantitative measure to characterize ULF behavior, comprising both total power and character of the spectra. In this report we introduce a ULF wave index and apply it to a correlative study with the relativistic electron dynamics.

### 2.2. Construction of a ULF wave index

We derive a ULF wave index to characterize the most intense fluctuations, using the spectral features of ULF power in the Pc5-6 band (from \( f_L = 1-3 \) mHz to \( f_H = 7-8 \) mHz), averaged over 1 hour from a global array of stations in the Northern hemisphere. We use data from the following global magnetometer arrays:

- INTERMAGNET (www.intermagnet.org),
- MACCS (space.augsburg.edu/space), and
- CPMN (denji102.geo.kyushu-u.ac.jp/denji/obs),

as well as data from some other selected observatories in Iceland and Arctic Russia (magbase.rssi.ru), with 1-min time sampling. A map with station locations is shown in Figure 1.

The data were inspected for quality and de-spiked. Any daily files with strong interference were purged from the database. The Nyquist frequency for 1-min sampling period is 8.3 mHz. The data have been detrended with a cut-off frequency 0.5 mHz and converted into a geocentric (X,Y) coordinate system. For any UT hour, the magnetic stations in the chosen MLT sector (from LT\(_1\) to LT\(_2\)), and in a selected CGM latitude range (from \( \Phi_S \) to \( \Phi_N \)) are selected.

The spectra of each horizontal component are calculated with the use of Filon’s integration method [Abramowitz and Stegun, 1972] in a 1 hour time window. The background noise spectral content may be estimated in different ways as schematically illustrated in Figure 2. On a log-log scale the “colored-noise” spectrum \( F_N(f) = F_0(f/f_0)^{-\alpha} \) is a straight line. The log\( F_N(f) \) is approximated by a straight line using the LINFIT IDL function (it fits the paired data to the linear model by minimizing the chi-square error statistics \( \sigma^2 \)) in the frequency band from \( f_L = 1 \) mHz to \( f_H = 8 \) mHz. The background spectrum is considered as \( F_N(f) = F_0(f) \). The bump above the discrimination line is
considered as a contribution from a narrow-band signal. Alternatively, the noise spectrum can be approximated by a straight line in a log-linear plot. Then, the discrimination line, separating the background and signal spectra, is considered as 
\[ \log F_B(f) = \log F_N(f) - \sigma \] (Figure 2).

The frequency range selected for the ULF index construction is bounded by the lower and upper frequencies, \( f_L \) and \( f_H \). Noise spectral power in this frequency range is calculated at each \( j \)-th station as the area beneath the discrimination level

\[ N_j = \int_{f_L}^{f_H} F_B(f) df \]

Signal spectral power is the area of the bump above the discrimination level (or background spectrum \( F_B \)), that is

\[ S_j = \int_{f_L}^{f_H} (F(f) - F_B(f)) df \]

The global ULF wave index is calculated from the band-integrated total power \( T_j = S_j + N_j \) at each station as follows

\[ T = \frac{1}{N} \sum_{i=1,N} T_j \]

In a similar way the total power of noise and signal components are defined

\[ S = \frac{1}{N} \sum_{i=1,N} S_j \quad N = \frac{1}{N} \sum_{i=1,N} N_j \]

Here the summation is performed with respect to all \( N \) stations where the power of the signal is above \( K \times \max \{ T_j \} \). The threshold parameter \( K \) may be reasonably chosen between 0.5 and 1.0 (the latter case corresponds to the selection of one station only with maximal amplitude).

The power index is augmented by a ULF sub-index to discriminate between broad-band and narrow-band ULF waves. The ratio between signal and total powers is calculated as follows:

\[ R = \frac{S}{T} \] . Here \( R \) varies in the range 0-1, and when \( S=N \), \( R=0.5 \).

For the additional verification of the discrimination of broad-band and narrow-band variations additionally an algorithm, based on the ratio \( R_G = T_{narrow}/T_{wide} \) between the wave power in a narrow band \( T_{narrow} \) and wide band \( T_{wide} \), has been applied.

Additional hourly ULF wave indices

Ground magnetic fluctuations are not always a perfect image of the ULF fluctuations in the magnetosphere. For example, there is a class of ULF waves, called storm-related Pc5 pulsations, that occur at the recovery phase of magnetic storm in the dusk and noon sectors of the magnetosphere. These ULF waves are generated by the ring current protons via various kinds of drift instabilities [Pilipenko, 1985]. Despite their high amplitudes in the magnetosphere, these pulsations are rarely if ever seen on the ground because of their small azimuthal scales, that cause effective screening by the ionosphere. Thus, the ground global
This wave index and pertinent sub-indices, coined the GEO ULF-index, are calculated from 1-min 3-component magnetic data from the geostationary GOES satellites to quantify the short-term magnetic variability in the region of geostationary orbit.

To quantify the short-term IMF variability, the interplanetary ULF index was estimated using 1-min data from the interplanetary satellites Wind, ACE, and IMP8. The data from these satellites were time-shifted to account for the ballistic propagation (either parallel or Weimer et al., [2003] technique) of the solar wind from the satellite location towards the magnetosphere.

**Validation of the ULF wave index**

To demonstrate the significance of this new index, as a first validation test, for some storm intervals we analyze the variability of the IMF, solar wind, and electron radiation near the geosynchronous orbit, together with existing static indices and the ULF wave index. This comparative analysis will elucidate the role of ULF turbulence in the particle response to solar wind forcing and demonstrate the merits and disadvantages of the wave index.

The following parameters have been used for the calculation of ULF index. The selection of magnetic stations has been made from LT=05 to LT=15, and in a CGM latitude range from Φ_s=60° to Φ_n=75°. The frequency range is from f_1=2.5 mHz to f_2=7.0 mHz, the discrimination level was estimated by a linear fit in the frequency interval f_1=1 mHz and f_2=8 mHz. The threshold parameter K=1.0. The data from interplanetary satellites have been time-shifted according to the parallel ballistic propagation model.

**1994 March-April**

The overall space weather parameters, space radiation and ULF activity during the extended period January-April 1994 as characterized by the Dst index, solar wind velocity V and plasma density N_p, together with relativistic (>2 MeV) electron fluxes J_e (count/cm²/sec/ sr) at GOES-7 (~94°W) are shown in Figure 3.

For this period the O’Brien database with hourly noon-reconstructed relativistic electron fluxes J_e (#/cm²/s/sec/ sr) at geosynchronous monitor GOES-8 (~75°W) is available, shown in the fifth panel in Figure 3. As compared with raw electron data the proxy-noon fluxes have no diurnal variations.

The sixth panel shows the ULF ground power index (log_{10}T) calculated from the global array of ground stations. Some diurnal variations of the global ULF index are caused by the lack of stations in the Russian sector.

The bottom panel shows the GEO ULF index calculated from the magnetometer data from GOES-7 (however, the Hp component only was available). A surprisingly good overall correspondence can be seen between the time dynamics of the global ground ULF index and the local ULF index at geosynchronous orbit.

During this period several magnetic storms with various intensities, from Dst~50nT to Dst~200nT, are observed. Long-term enhancements of J_e are observed after each storm. However, no association between the storm intensity (Dst) and J_e can be seen. At the same time, much better similarity between the ULF index and J_e exists. In what follows we consider one interval in greater detail.
During the selected interval in March-April 1994, namely 03/03 (DOY=63)-04/25 (DOY=115), 3 magnetic storms are observed (Figure 4):
- weak (Dst~100 nT) storms on 03/08 and 04/02;
- strong (Dst~200 nT) storm on 04/17.

GOES-8 noon-reconstructed relativistic electrons fluxes demonstrate also 3 enhancements, after each storm, with a peak delay about 1-2 days. But, surprisingly, a sustained intense increase of \( J_e \) (above \( 10^5 \)) is observed after the weak storms, whereas the increase after the strong storm on 04/17 is much shorter and less intense (up to \( 10^3 \) only).

At the same time, the electron behavior matches well the variations of the global ULF-index (forth panel in Figure 4): after the first storm this increases much more substantially and for a longer period than after the second storm. The time variations of the total power index \( J \) and of the narrow-band part of spectrum \( S \) are rather similar. The fraction of the narrow-band component \( R \) (not shown) has a slight tendency to increase during the recovery phases of magnetic storms.

Comparison with the O’Brien \( B \)-index, shown in the third panel, indicates a good correspondence between this index and the new ULF index. It should be remembered that the \( B \)-index is smoother because of its 2-hour averaging window as compared with the 1-hour window used for production of the ULF-index.

Both the ULF-index and \( B \)-index correspond well (correlation coefficient \( r \approx 0.7 \)) to the ULF power index calculated from GOES-7 data (Hp component), shown in the bottom panel of Figure 4.

During two weak storms in March-April 1994 period geostationary satellites suffered numerous anomalies due to magnetospheric relativistic electrons (“killer” electrons) [Pilipenko et al., 2004]. Bursts of relativistic electron fluxes on 03/10-16 and 04/04-16 produced a swarm of malfunctions onboard the geostationary satellites. As Figures 3 and 4 show the “killer” electron flux has a time delay about 1-2 days with respect to the ULF wave index, therefore, the ULF wave index could be used as a “precursor” of the risk of geostationary satellite malfunctions during the declining phase of the solar cycle.

**Space Weather Month: September 1999**

Further we consider Space Weather Month (September 1999). Figure 5 shows the space weather parameters, such as the solar wind velocity \( V \), plasma density \( N_p \), IMF magnitude \( B \), the north-south IMF component \( B_z \), and the Dst index, together with the relativistic electron fluxes \( J_e \) (>2 MeV) at GOES-10 (~104°W) during the period from 09/10 (DOY=253) to 09/30 (DOY=273). During this interval a strong magnetic storm occurred on 09/22 (Dst = -164 nT) and 3 weak storms (Dst about –50 nT) occurred on 09/12, 09/16, and 09/27.

The main storm was caused by a shock (solar wind pressure pulse up to 15 nPa), followed by a large interplanetary magnetic cloud with south to north field rotation. The strong IMF \( B_z \) early in the magnetic cloud drove a major magnetic storm on 09/23. Both strong and weak storms were accompanied by high solar wind streams, enhancements of the solar wind density and IMF magnitude, and negative IMF \( B_z \) excursions (Figure 5). The increases of \( V_{sw} \) and \( N_p \) were nearly the same during both strong and weak storms, up to 650 km/s and 40#/cm³, correspondingly, but the \( B_z \) excursion and kinetic pressure were larger for the strong storm.

The onset of the strong storm 09/22 is shown in magnetograms of the X component from ground stations in the latitudinal range
60°–75° together with 3-component magnetograms from the GOES-10 and ACE (time shifted) satellites (Figure 6). These plots have been produced for each day to verify the quality of the data before the ULF index construction.

GOES-10 detected several substantial increases of relativistic electron fluxes (>2MeV) from $\sim 10^2$ to $\sim 10^3$ on 09/14 and a gradual increase starting on 09/27. Similar behavior is observed at GOES-8 (not shown), but the overall level of electron fluxes is lower, and were more gradual. The sudden drop to $\sim 10$ on 09/22, observed one day before the storm onset on both GOES satellites, is puzzling. It is not likely to be explained by the adiabatic compression of the magnetosphere.

A comparison of characteristics of ULF activity with relativistic electron dynamics is given in Figure 7. Global ground ULF indices, both total power ($\log_{10} T$) and narrow-band power ($\log_{10} S$), demonstrate 3 increases comparable in magnitude on 09/12, 09/16 and 09/27, indicating that this series of substorms was succeeded by very intense and long-lasting monochromatic Pc5 activity. At the same time, the main magnetic storm 09/22-23 was accompanied by short-lived Pc5 waves only. This analysis shows, perhaps unexpectedly, that a significant increase of relativistic electron flux at geostationary orbit (up to 2-3 orders of magnitude) is observed not during the magnetic storm, but during the substorm period after weak storms. The feature of these intervals is a long-term elevated level of the ULF index, caused by the occurrence of very intense Pc5 pulsations.

The GEO ULF index, characterizing the intensity of ULF activity at geostationary orbit (forth panel in Figure 7), also shows 3 enhancements during magnetic storms, similar to the ground global ULF-index (correlation coefficient $r \approx 0.75$). However, some ULF intensification intervals (e.g., 09/17) are missed by the satellite. It seems that the ground ULF index better characterizes the global ULF activity than the local satellite index.

Increases of the ULF index in general coincide with increases of the IMF ULF index calculated from the time-shifted ACE data (third panel in Figure 7). This may indicate the existence of an additional factor controlling the ULF activity in the magnetosphere – the level of seeding IMF fluctuations in the solar wind upstream the magnetosphere.

**Discussion: So what and what is next?**

The analysis of the period with disturbed space weather in April 1994 has shown, rather surprisingly, that sustained intense increases of GOES-8 noon-reconstructed relativistic electrons fluxes up to $\sim 10^4$ occurred after the weak storm (Dst≈100nT), whereas the increase after the strong storm (Dst≈200nT) is much shorter and less intense (up to $\sim 10^3$ only). The electron behavior matches well the variations of the global ULF-index: after two weak storms this index increases much more substantially and for a longer period than after the strong storm. Both the ULF wave index and B-index correspond well to the ULF wave power index at geosynchronous orbit calculated from GOES-7 magnetometer data.

Analysis of Space Weather Month activity also has shown that a significant increase of relativistic electron flux (up to 2-3 orders) at geosynchronous orbit is observed not during the main magnetic storm (Dst≈160nT), but during the substorm periods after weak storms (Dst≈50nT). The feature of these intervals is an elevated level of the ULF index, caused by the occurrence of very intense Pc5 pulsations. The GEO ULF-index, characterizing the intensity
of ULF activity at geostationary orbit, also shows 3 enhancements during magnetic storms, similar to the ground global ULF-index.

The ULF sub-index $R$, intended to discriminate between broadband and narrow-band ULF waves, has not demonstrate consistent results and not shown here. For some stations $R$ grew during a magnetic storm interval indicating that at the main phase the storm-related ULF activity is dominated by wide-band irregular oscillations, whereas at the recovery phase this activity is dominated by narrow-band ULF waves. Both $R$ and $R_G$, estimated as the ratio between total power in a 3-7 mHz and 0.2-8.3 mHz bands, gave similar results. However, on a global scale, the irregular variations of $R$, commonly in the range 0.3-0.6, were larger than a general trend. More studies are necessary. The usage of the technique to discriminate polarized and non-polarized components might be helpful in further development of the ULF index.

Increases of the ground ULF index in general coincide with increases of the IMF ULF index. This may indicate that there exists an additional factor controlling the ULF activity in the magnetosphere, besides solar wind velocity [Engebretson et al., 1998], namely, the level of seeding IMF fluctuations.

During the March-April 1994 storms geostationary satellites suffered numerous anomalies from “killer” electrons. Relativistic electron flux has a time delay ~1-2 days with respect to the ULF-index. Thus, this index could be used as a “precursor” of the risk of geostationary satellite anomalies during the declining phase of the solar cycle. For that, probably, a cumulative ULF-index should be constructed, taking into account the effective acceleration time.

The observed correspondence between the new ULF wave index and relativistic electron dynamics is consistent with the results of the studies by O’Brien et al., [2000] and Mathie and Mann, [2001]. However, in this report we have attempted just to demonstrate a usefulness and easiness of the use of the ULF wave index for the studies of the high-energy particle energization in the magnetosphere, but we do not claim that the drift resonant interaction with ULF waves is the only mechanism of the relativistic electron acceleration (see, for example, Reeves et al., [2003]).

Though the existing database of the ULF index is already suitable for statistical analysis, in the future we plan to update the technique of index construction. More stations will be included in the analysis, comprising CANOPUS, IMAGE, and Greenland arrays.

Earlier, we have introduced the technique of virtual magnetograms for monitoring the transient or bursty response of the geomagnetic field to solar wind forcing in key magnetospheric regions [Pilipenko et al., 2002]. Virtual magnetograms for a fixed reference system were reconstructed by fitting and interpolation of magnetograms from distributed magnetic stations. The databases of virtual magnetograms could be a useful additional tool for the analysis of space weather events.

**Conclusion**

A new hourly index, analogous to geomagnetic indices, has been derived from ground and satellite magnetometer data. A wide range of space physics studies, such as substorm physics, relativistic electron energization, solar wind-ionosphere coupling, etc. may benefit from the introduction of the wave indices. The wave index has been validated by comparative analysis of relativistic electron enhancements during selected storm intervals.
A scientific consortium comprising the Space Physics Laboratory of Augsburg College, Space Environment Research Center of Kyushu University, and Institute of the Physics of the Earth provides the space community with a new ULF wave index. The database for the interval 1994-2000 is freely available via anonymous FTP at the following site for testing and validation: space.augsburg.edu, in the folder: /pub/MACCS/ULF_Index/. Comments and requests for specific intervals or parameters of the ULF index construction are welcomed.

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KOZYREVA ET AL.: NEW ULF WAVE INDEX
Figure 1. Map of the ground magnetic stations used for calculation of the global ULF wave index: CPMN (boxes), INTERMAGNET (filled circles), MACCS (diamonds), and other stations (triangles).

Figure 2. Schematic plot of the technique for the discrimination of signal and noise from the power spectral density of ULF variations.

Figure 3. Overall magnetic activity and noon-reconstructed electron intensity at GEO for the period January-April 1994 as characterized by: Dst; solar wind velocity V; solar wind density Np; GOES-7 integral electron (>2 MeV) fluxes; GOES-8 noon-reconstructed fluxes \( J_e \); the ground wave power ULF-index \( T \); and the wave power ULF index derived from Hp component onboard GOES-7 (\( T_{GEO} \)).

Figure 4. Comparison of GOES-8 noon-reconstructed relativistic electron fluxes (>2 MeV) with ULF activity for period March-April 1994 as characterized by: Dst; the GOES-8 noon-reconstructed fluxes of electrons >2 MeV; O’Brien’s B-index; the ground ULF-index (total power \( T \) and narrow-band power \( S \)); and the wave power ULF indices \( T_{GEO} \) and \( S_{GEO} \) derived from Hp component onboard GOES-7.

Figure 5. The space weather parameters during the Space Weather Month period (09/10-09/31): V; Np; B; Bz; Dst; and GOES-10 integral electron (>2 MeV) electron fluxes \( J_e \).

Figure 6. The magnetograms of the X component from the stations in the latitudinal range 60°–80° for 1999/09/22 together with 3-component magnetograms from GOES-10 and ACE (time shifted) satellites. The noon (open triangle) and midnight (dark rhombs) for each ground station are indicated. Codes and CGM coordinates are indicated at the right.

Figure 7. Comparison of electron fluxes with the storm and ULF wave indices (total power \( T \) and narrow-band power \( S \)) during the Space Weather Month (09/10-09/31): Dst; GOES-10 integral electron (>2 MeV) electron fluxes \( J_e \); the IMF wave index from the propagated ACE data; the GEO ULF wave index derived from 3-component magnetometer onboard GOES-10; and the global ground ULF index.
Discrimination level

Logarithmic Power Spectral Density

Signal

Noise

Linear fit

\( f_1 \) \( f_L \) \( f_H \) \( f_2 \)