Updated ULF Wave Power Index for Space Weather Applications

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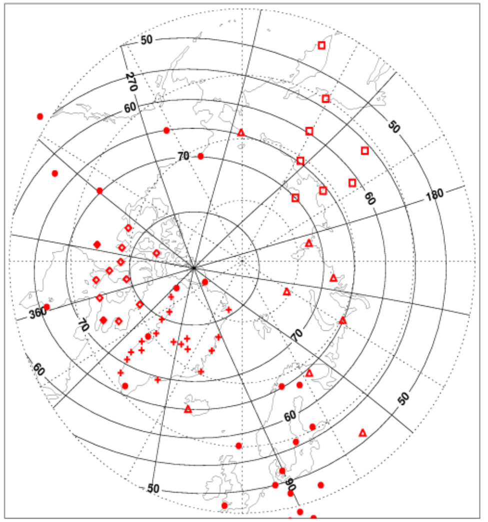
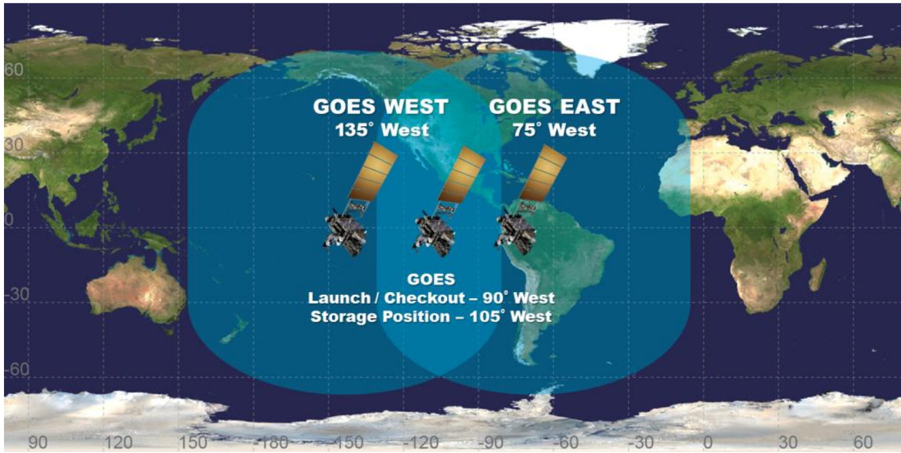
Physical background and necessity of ULF indices

- The interaction between the solar wind (SW) and terrestrial magnetosphere is the primary driver of many processes in the magnetosphere. This interaction has often been viewed using the implicit assumption of laminar plasma flow.
- However, most energy transfer processes in the magnetospheric boundary regions have a sporadic/bursty character, which is not accounted for by commonly used geomagnetic indices and OMNI parameters.
- 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.
- Therefore, much of the turbulent nature of near-Earth plasma processes can be monitored with ground or space observations in the ULF range. To quantify the level of ULF turbulence / variability of the geomagnetic field, IMF, and SW plasma, we have introduced a set of ULF wave power indices.

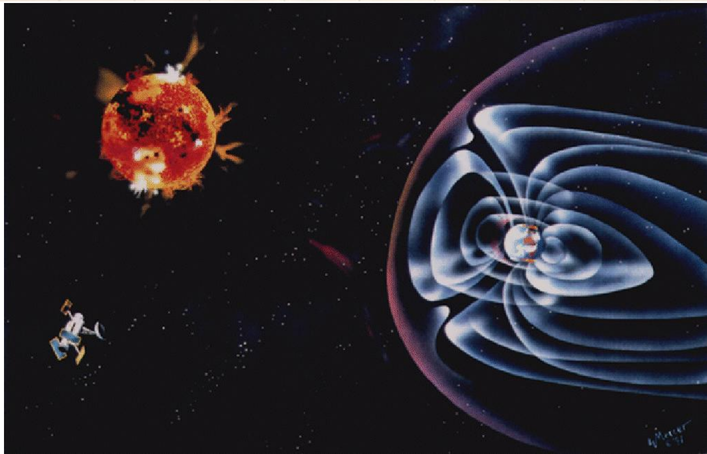
Set of the ULF Wave Power Indices



GROUND ULF wave index as a proxy of global Pc5 activity (2-7 mHz) is reconstructed from 1-min data from ALL magnetic stations in the Northern hemisphere (INTERMAGNET, MACCS, MAGDAS, Arctic Russia, etc).

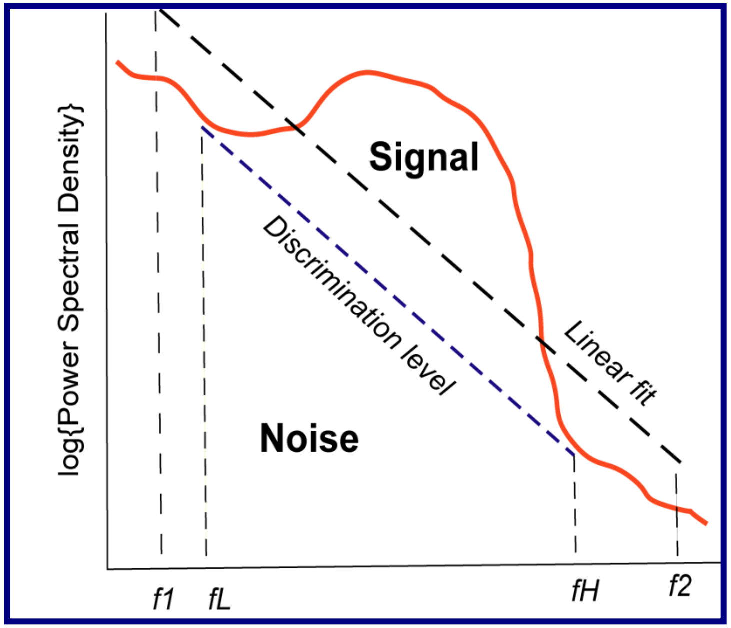


GEO ULF wave index is calculated from 1-min 3-component magnetic data from GOES satellites to quantify the magnetic variability at the geostationary orbit.



INTERPLANETARY ULF wave indices to quantify the IMF & SW variability are calculated from 1-min data of interplanetary satellites (OMNI) database. The data are time-shifted to the terrestrial bow shock.

Algorithm of ULF wave index construction



The algorithm selects the peak value of band-integrated spectral powers of 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 50^0 to 70^0 geomagnetic latitudes;

Algorithm of the ULF wave index relies on the estimate of the ULF power **in a 1-hour running window** in the **2-7 mHz band**.

The final total power index (T) index is normalized in such a way to have dimension of [nT].

Total band-integrated power (T)

$$T = \int_{f1}^{f2} F(f)df$$

Set of the wave power indices from ground, geostationary, and interplanetary monitors

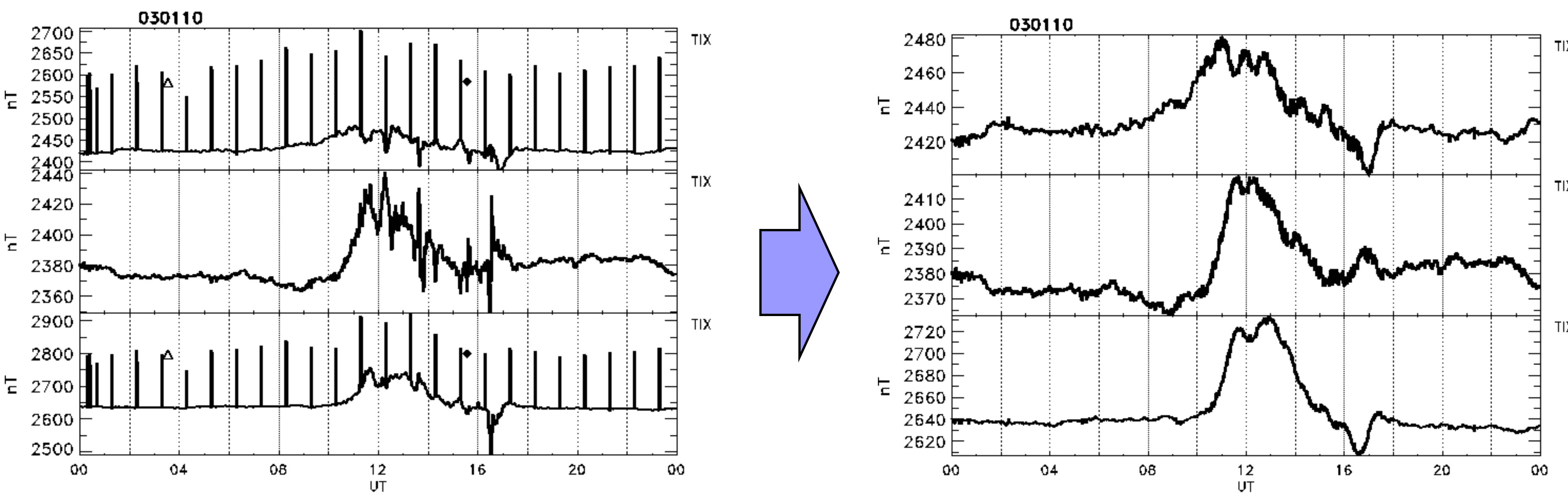
Ground ULF Tgr	GEO ULF Tgeo	IMF ULF Timf	SW ULF Tden

Data pre-processing

The hardest part of the index production is compilation of database from all available magnetometers, reading data in various formats, etc. Pre-processing demands a lot of manpower, because even INTERMAGNET data are not 100% perfect, and it includes:

- elimination of spikes
- level jumps,
- interference,
- short data gaps.

Automatic recognition and correction of anomalous events has been provided by application of mathematical methods based on the theory of discrete mathematical analysis (DMA).



Website with the ULF-index database http://ulf.gcras.ru/

We have made the database freely available via the specially designed website (including anonymous FTP). The ULF index database has been compiled for the period **1991-2015**.
The website provides a user the possibility:

- ❑ to browse and download monthly plots with basic space weather information, including the ground, geosynchronous, and interplanetary ULF indices;

- ❑ to browse and download daily plots with high-latitude world-wide magnetometers, GOES spacecraft magnetometers, and basic solar wind and IMF parameters from OMNI database;

- ❑ to download monthly ASCII files with basic space weather information, including the ground, geosynchronous, and interplanetary ULF indices.

- ❑ the website provides a list of downloadable journal publications and conference talks related to the use of ULF wave index in space weather studies.

- ❑ Description of the IDL computer algorithm used during the index production is given also.

- ❑ Researchers interested in long-term statistical studies can get access via FTP to zip-compressed monthly files with basic space weather information, including ULF index.

File format

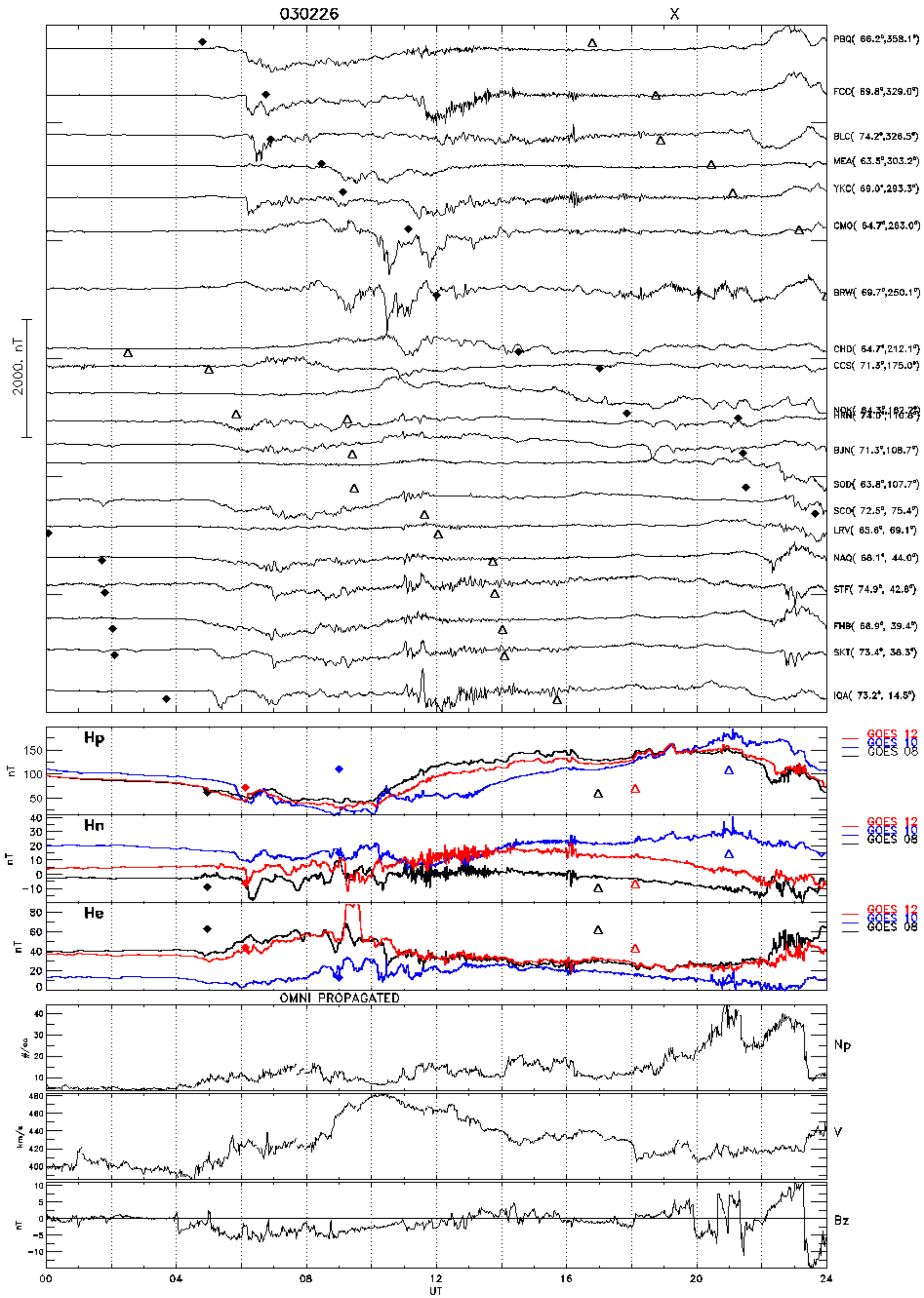
The provided information is in monthly ASCII files with a simple multi-column structure.

To facilitate data analysis output files hold key SW/IMF parameters and Dst index (all 1-hour averaged).

JAN 2003

DD	HH	Tgr	Tgeo	Timf	Tden	V	N	Bz	Dst
01	00	4.80	0.34	0.82	4.32	407.0	5.0	2.0	-4.
01	01	4.17	0.27	0.71	3.12	425.0	5.5	0.2	1.
01	02	5.55	0.21	NaN	NaN	420.0	5.7	-1.5	1.
01	03	9.54	0.43	1.23	2.58	424.0	5.3	-0.5	-6.
01	04	19.89	0.62	0.56	1.38	429.0	6.6	2.1	-6.
01	05	23.06	0.36	0.64	1.96	425.0	6.4	0.7	-2.

Daily plots



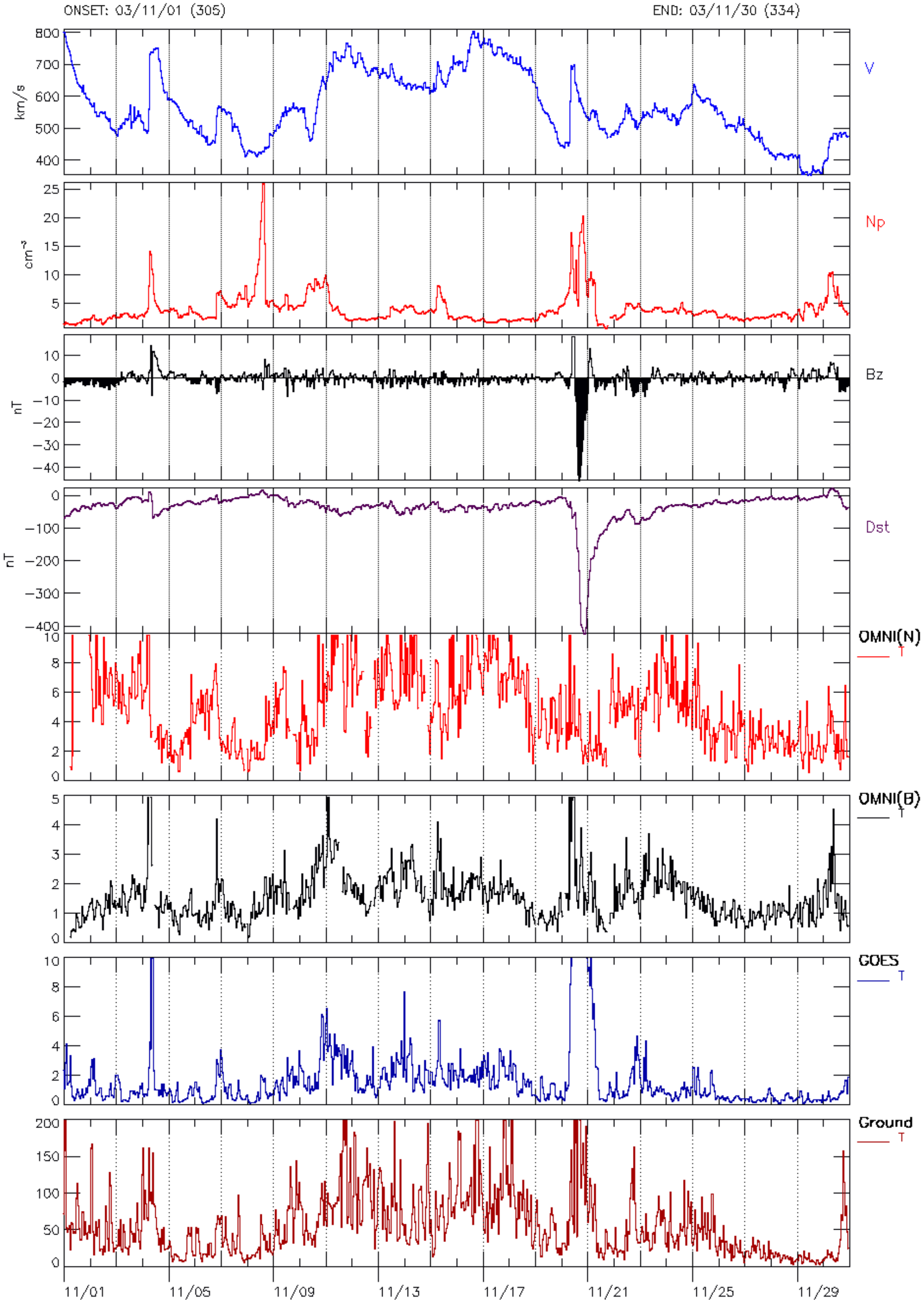
The database holds **daily plots** with:

-magnetograms from all stations selected by the algorithm,

- 3 component GOES magnetograms from all available spacecraft,

- key SW/IMF parameters: velocity, density, IMF Bz.

These plots are very helpful even for studies non-related to ULF index



Monthly plots

The database includes monthly plots of 3 sets of ULF indices, together with key space weather parameters: V, N, IMF Bz, Dst.

Possible applications

There are many space weather related problems, where a rough proxy of the level of MHD turbulence might be of key importance:

- **ULF wave index and "killer" electrons.** Relativistic electron energization is not directly related to the intensity of magnetic storms, but correlated with time-integrated ULF wave index. This confirms the importance of a "magnetospheric geosynchrotron": long-lasting magnetospheric ULF turbulence energizes seed electrons up to relativistic energies

- **Solar wind-magnetosphere coupling:** interplanetary turbulence in driving the magnetosphere by the IMF/SW must not be ignored. The magnetospheric response may be different for the laminar and turbulent SW/IMF flow;

- **IMF/SW control of the magnetospheric ULF wave activity:** How significant are irregular SW plasma density enhancements?

- **Substorm onset:** The break-up may be preceded by an enhanced level of ULF power?

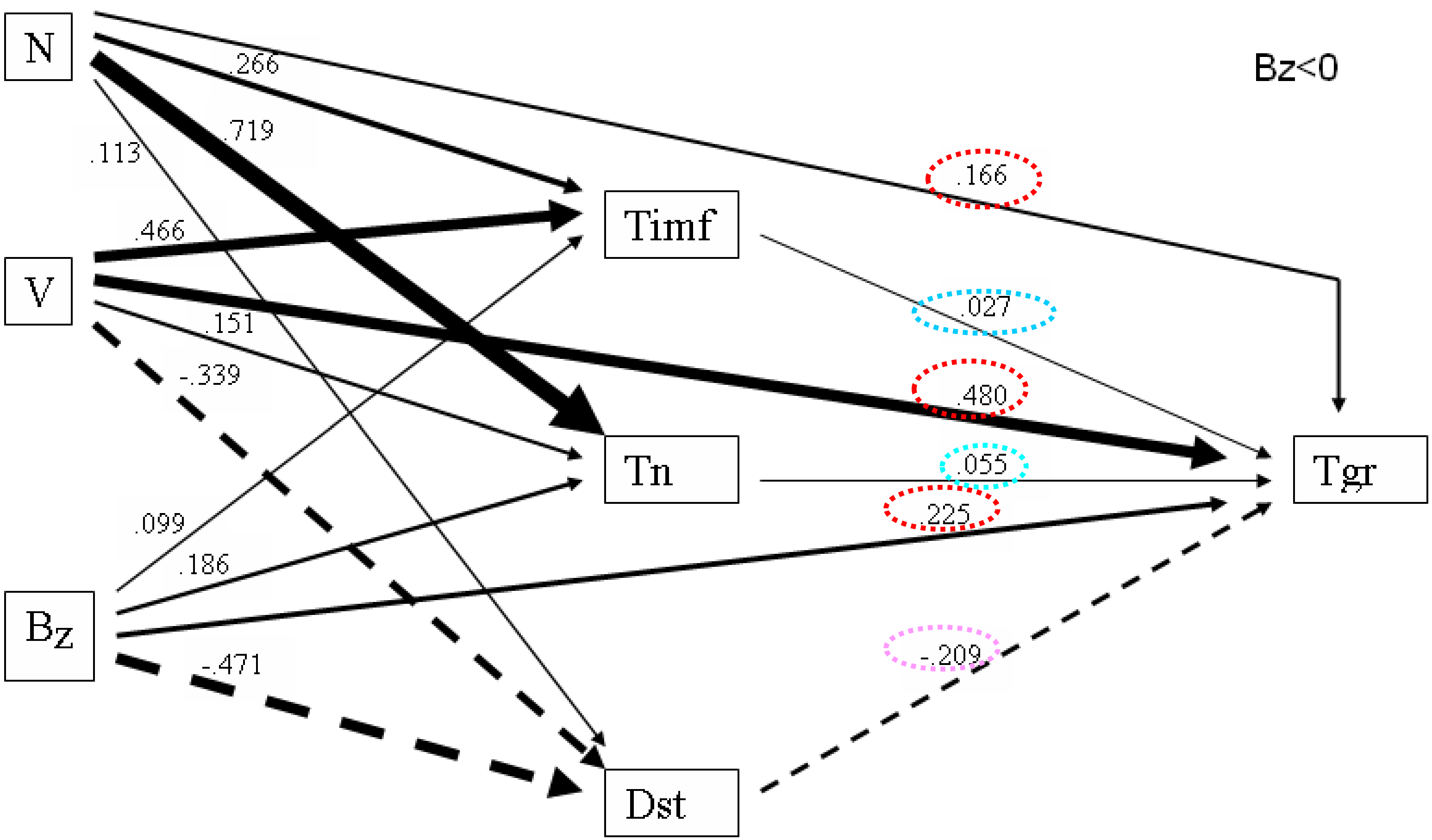
- **Ring current formation:** What is the role of particle diffusion?

- **The search for electromagnetic precursors of earthquakes:** Magnetospheric background

The ULF index should be taken into account by any statistical space weather model

Path analysis of the drivers of ground ULF wave activity

Path analysis is a visualization of multiple regression - a diagram showing possible causal relationships between the variables. The relative strengths of the path coefficients (standardized regression coefficients) are used to determine which direct & indirect paths have the most influence on the dependent variable.

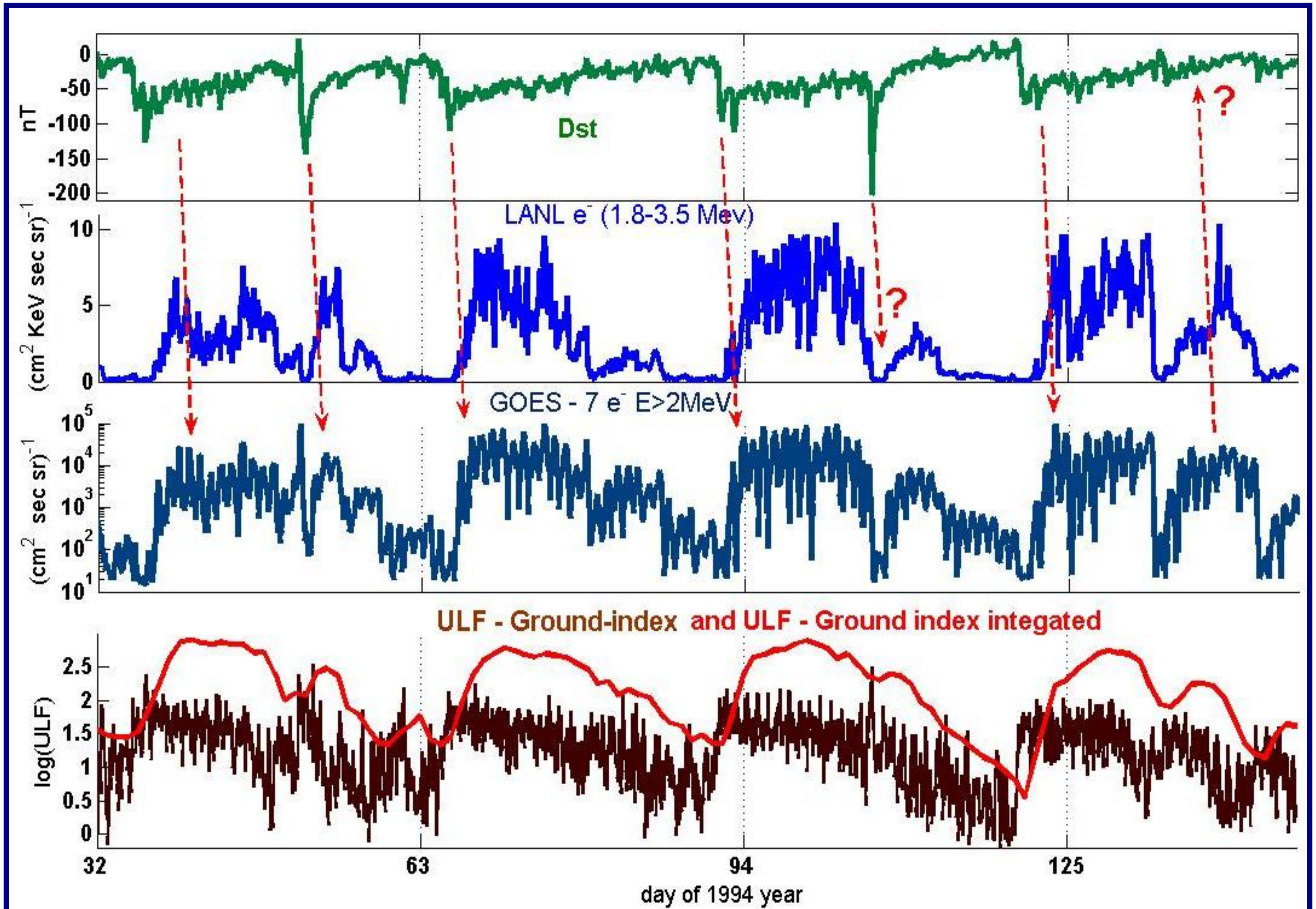


V has the greatest direct effect, with some contribution from Bz and N.

Also there are contributions from indirect paths via IMF/SW turbulence and RC

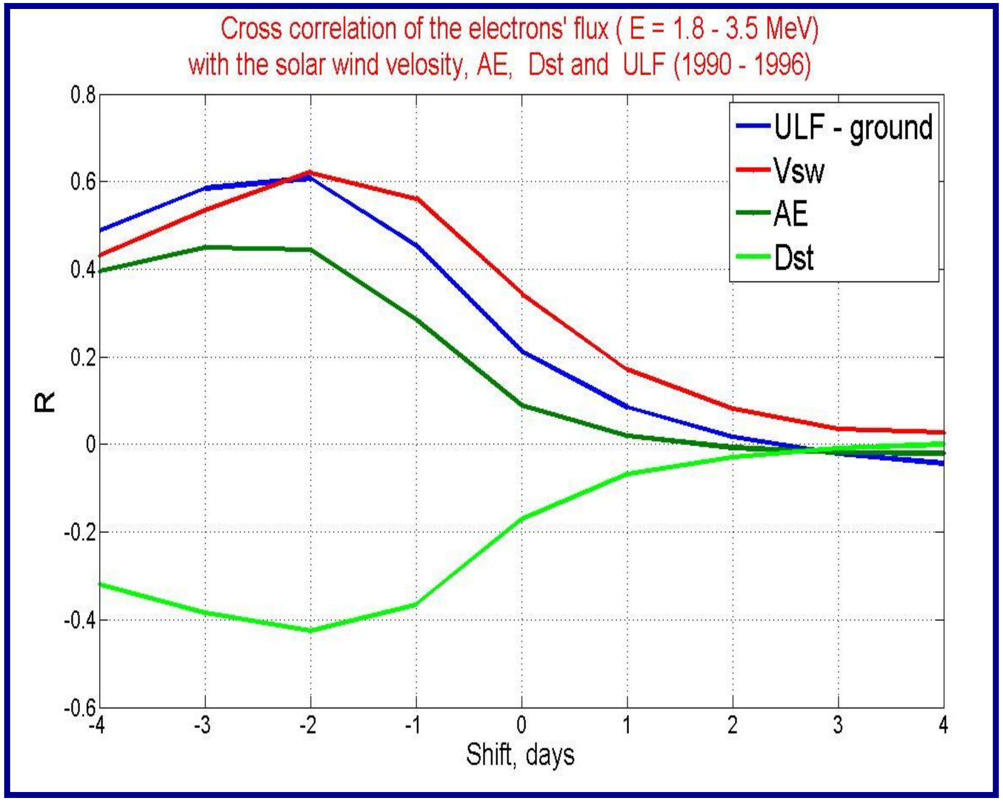
ULF wave activity and relativistic electron acceleration

Surprisingly, a sustained increase of the relativistic electrons (E>2 MeV) fluxes up to 2-3 orders is observed after weak storms (Dst~-50-100nT), whereas the increase after strong storms (Dst~-200nT) is much shorter and less intense. Moreover, there are events when electron bursts occur without storms.

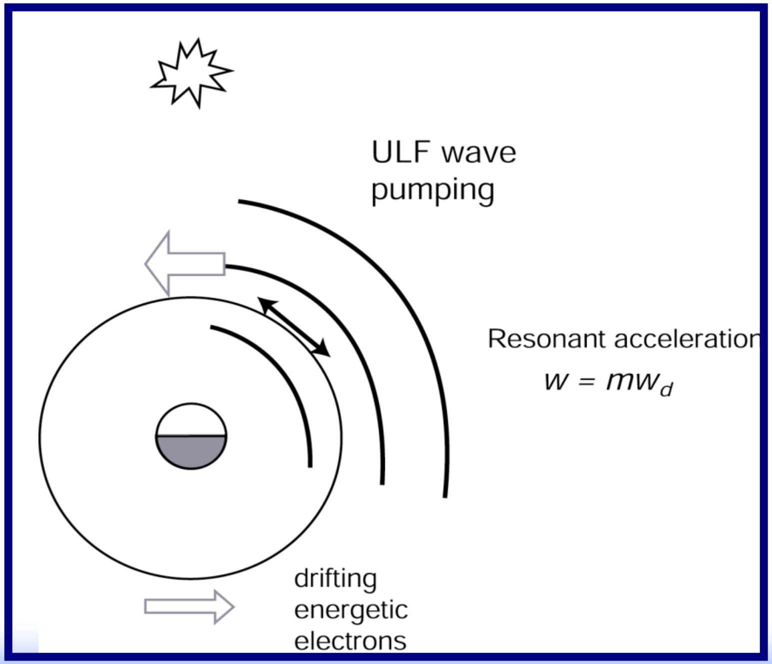


Relativistic electrons would not appear in the non-turbulent magnetosphere!?

Geosynchrotron: Are ULF waves an intermediary between the SW and "killer" electrons?



Mechanism of 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 a multiple of the electron drift period.



High solar wind velocity, as well as elevated level of ULF wave activity, precede the growth of relativistic electron flux by ~2 days.

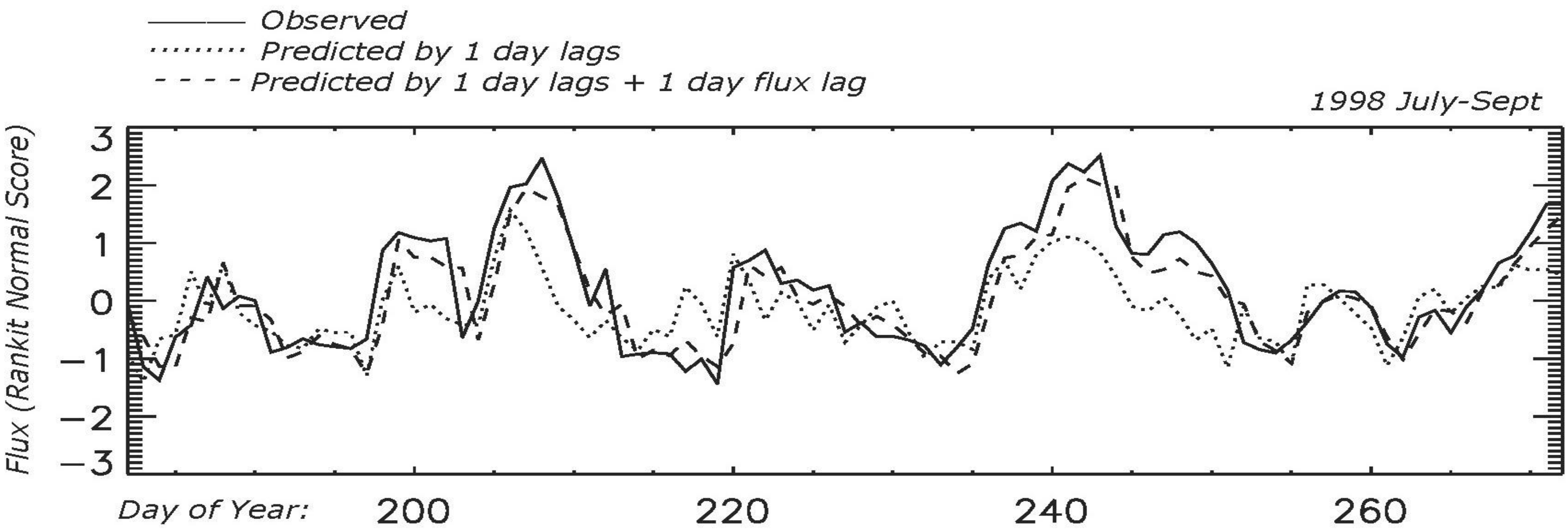
Predictive Models of Relativistic Electron Flux: Multiple Regression Analysis

The daily maximum GEO relativistic electron flux J_R can be predicted with a set of variables including previous day's flux, seed electrons, SW V & N, AE, IMF Bz, Dst, and ground ULF - VLF power. As predictor variables are intercorrelated, **multiple regression analysis** is to be used to determine which are the most predictive when other variables are controlled. The predicted response Y_i, is a linear combination of the parameters X_i multiplied by their regression coefficients b_i

$$Y_i = b_0 + \sum b_i X_i$$

Correlations between observations and predictions ranged ~0.7-0.9. Path analysis of correlations between predictors suggests that **SW and IMF parameters affect flux through intermediate processes such as ring current, AE, and ULF/VLF activity**.

Combined effect of ULF & VLF waves shows synergistic interaction: each increases influence of the other.



Impact of the Level of Solar-Wind Turbulence on Auroral Activity

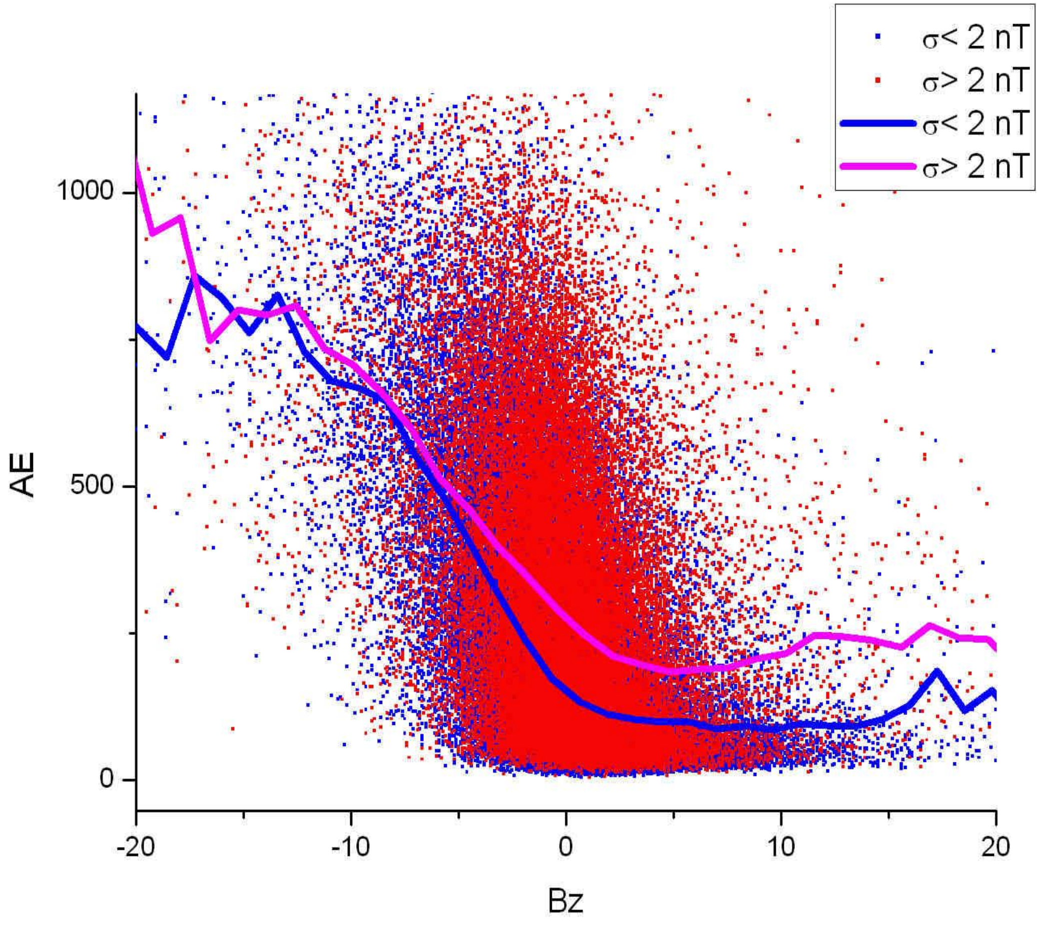
Though the SW is turbulent, in studies of SW-magnetosphere coupling this fact is ignored. However, a laminar flow is not an average of a turbulent flow! SW may drive the magnetosphere in a different manner, depending on the upstream turbulence level. Naive expectation is that when the SW is more turbulent, the effective degree of its coupling to magnetosphere is higher [*Borovsky and Funsten*, 2003].

Auroral response is compared with similar strength of IMF driver (Bz) for **laminar** (σ\{Bz\}<2nT) and **turbulent** (σ\{Bz\}>2nT) flow.

Average AE for the turbulent SW are higher than for the laminar solar wind!

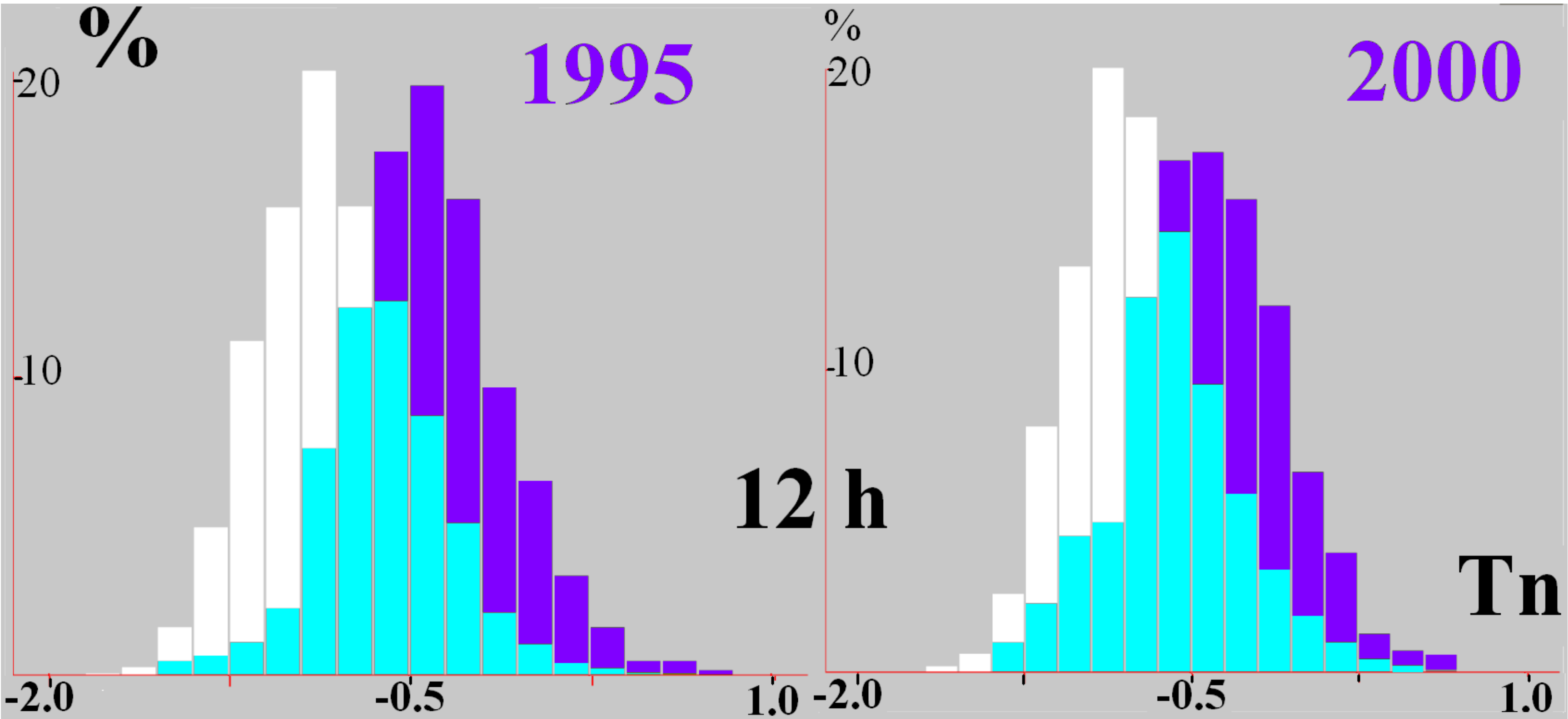
This difference is most significant for **northward Bz**, when the viscous interaction is expected to be dominant over the reconnection.

The magnetosphere is driven more strongly when the level of SW/IMF turbulence is high (under the same average interplanetary parameters)!



Some features of the SW-IMF behavior before magnetic storms

Weak irregular increase of the SW density is observed ~1-2 days before storm commencement. Medium-term precursors of severe space weather?



Statistical distribution of *Tn* index:

-yearly distribution (white)

-distribution during 12-hour intervals before storm onsets (blue).

Green color denotes intersection between them.

Problems, drawbacks, perspectives,…

We permanently update the ULF index database, making improvements in the output file format, visualization, and expanding the number of magnetic stations used.

So far, the index does not discriminate **periodic oscillations vs. steep irregular variations**

Relativistic electron flux has time delay ~2 days with respect to the ULF-index. Thus, this index could be used as a “precursor” of the risk of GEO satellite anomalies. For that **cumulative ULF-index could be constructed** (taking into account effective acceleration time).

ULF index can be re-calculated **upon request** with different parameters, region, stations, etc.

Using a similar approach, **ULF index can be constructed in other ULF frequency bands,** using data from world-wide array of search-coil magnetometers:

- Pc3 index (10-100 mHz), characterizing the upstream turbulence in the terrestrial foreshock region**;**

- **Pc1 index** (~0.1-1 Hz) to characterize the global intensity of EMIC waves, responsible for depleting the outer radiation belt;

We expect a feedback from all interested researchers:
any suggestions, constructive criticisms, etc., are welcomed!

Preliminary conclusions

✓ Even provisional version of ground and interplanetary ULF power indices is a convenient and easy-to-use tool for visualization and statistical analysis of the SW – magnetosphere interaction with account for the turbulence aspects.

✓ Wave power index characterizes the ULF wave activity on a global scale better than data from selected stations subjected to unavoidable daily variations.

✓ ULF wave power, especially the cumulative index, characterizing the level of ULF turbulence in near-Earth space, is a good predictor for the relativistic electron dynamics. The ULF index should be taken into account by any statistical space radiation model.

✓ Iinterplanetary ULF index reveals an elevated variability of the SW prior to magnetic storms, which may be classified as medium-term space weather precursor?