STUDY OF THE OUTER RADIATION BELT OF THE EARTH
BY SEGMENTATION OF MULTI-DIMENSIONAL TIME SERIES*

Myagkova I.N., Dolenko S.A., Persiantsev I.G.
D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University,
Moscow, Russia, e-mail: irina@srd.sinp.msu.ru

Abstract. Study and prediction of the relativistic electron flux in the outer ERB is a complicated problem. This is due to the fact that Earth’s magnetosphere is a complex dynamical system. The state of this system can be described by a multi-dimensional time series, including various physical features - parameters of interplanetary magnetic field, solar wind, geomagnetic indexes, relativistic electron flux at geostationary orbit etc. Here we consider the approach to investigation of time series characterizing the dynamics of the outer ERB with the help of machine learning algorithms. To separate out such regions, in this study we used segmentation of multi-dimensional time series with the help of k-means clusterization algorithm and Kohonen neural networks. The initial data which are a multi-dimensional time series with delay embedding were split into three, four, and five clusters (segments) with Kohonen self-organizing map and k-means algorithm. The obtained variants of segmentation of the time series were compared to each other and correlated with various possible states of the outer ERB.

INTRODUCTION

The outer radiation belt of the Earth (OERB) is a part of inner Earth’s magnetosphere. It is well known that strong (more than two orders of magnitude) and abrupt changes of relativistic and sub-relativistic electron flux intensity in the OERB occur during magnetic disturbances due to arrival of both coronal ejections and high-speed solar wind streams to the Earth’s orbit (e.g. Tu et al., 2009). The intensity of the flux of relativistic electrons in the outer ERB is subject to the influence of solar wind (SW) and interplanetary magnetic field (IMF) parameters (e.g. Reeves et al., 2011), that are difficult to take into account (refer to Fig. 1 as an example).

Fig. 1. Time variations of solar wind speed, IMF (|B| and Bz), Dst and Kp indexes, relativistic electron flux (E>2 MeV) during August – September 2014.

* This study was supported by the Russian Foundation for Basic Research (RFBR), project no. 14-01-00293. Myagkova I.N. thanks RFBR project no 12-05-01030.
There is every reason to believe that there may exist several different basic states of the magnetosphere – significantly diverse regions in the phase space of the states of this dynamical system, for which the most efficient prediction models may be different. To separate out such regions, in this study we used segmentation of multi-dimensional time series with the help of Kohonen artificial neural networks (ANN), self-organizing maps (SOM), and with the help of k-means clustering algorithm.

Acceleration and losses of relativistic electrons of ERB in the Earth’s magnetosphere is an important fundamental problem in space physics (e.g. Friedel et al., 2002), so the main goal of our research is to improve understanding of the Earth’s magnetosphere dynamics. From the other hand, relativistic electrons may cause dangerous malfunction of the electronics onboard spacecraft and therefore they are often called killer electrons (Iucci et al., 2005, Pilipenko et al., 2006). So forecast of relativistic electron flux in OERB is an important practical task, and the second goal of this study is to improve our forecast.

METHOD AND INPUT DATA

In this study, we used the implementation of Kohonen ANN and SOM in the software package Deductor 5.3 – the Russian version of Loginom software (Loginom – analytical platform. http://loginom.basegroup.ru). The following network parameters were used: the network consisted of 16×12 hexagonal cells with Euclidean distance function; the initial learning rate was 0.5, the finishing learning rate was 0.1; training continued for 500 epochs. The number of obtained clusters varied from 2 to 5.

As input data, time series (TS) of hourly values of the following physical quantities were used:

1) Solar wind (SW) parameters in Lagrange point L1 between the Earth and the Sun:
   • SW speed $v$ (measured in km/s)
   • SW protons density $n_P$ (measured in cm$^{-3}$)
   • SW temperature $T_{rr}$ (measured in K)

   The data used was from ACE (Advanced Composition Explorer) spacecraft, measured by SWEPAM (Solar Wind Electron Proton Alpha Monitor) device.

2) Interplanetary magnetic field (IMF) vector parameters in Lagrange point L1 (measured in nT) in GSM system:
   • $B_x$, $B_y$, $B_z$ (IMF x-, y-, and z-components)
   • $B$ magnitude (IMF modulus)

   The data used here was also from ACE spacecraft, MAG device.

3) Geomagnetic indexes
   • Equatorial geomagnetic index Dst (measured in nT)
   • Planetary index Kp (dimensionless)

   The data used was from World Data Centre for Geomagnetism in Kyoto (Japan).

4) Relativistic electrons (>2 MeV) flux measured at geostationary orbit by GOES satellite.

   The considered data period was from November 1997 to March 2014.

   To account for the previous history of input features, delay embedding of all TS for 24 hour depth was used. Thus, each data pattern was a point in 200-dimensional feature space (8 TS × 25 hours), assigned to the latest point of the 25-hour window.

KOHONEN MAPS

Fig.2 displays the SOM obtained with the listed parameters for 5 clusters. Cell colors represent average value of the corresponding parameter for this cell. Brighter color corresponds to higher parameter value (please refer to the legend bar at the bottom of each map).

The obtained clusters were interpreted in the following way:

a) Cluster 0 (dark blue): minimum of electron flux, Kp and SW speed are also low; such a state was mainly observed during the extreme minimum in 2009;

b) Cluster 1 (light blue): electron flux is low but higher than in cluster 0; SW speed, Kp are similar to cluster 0; this cluster can correspond to low geomagnetic disturbance;

c) Cluster 2 (medium blue): here, the highest values of Kp index, Dst amplitude, SW speed, and B are observed, so this is possibly the main phase of magnetic storms;

d) Cluster 3 (green): higher values of electron flux, Kp and Dst than in cluster 2; this can be the beginning of the recovery phase;

e) Cluster 4 (red): maximal values of electron flux; Dst amplitude and Kp are low again; this cluster corresponds to the end of the recovery phase.
In order to test this interpretation, we calculated the number of samples (measurement hours) assigned to each cluster, and compared it to the number of magnetic storms with an amplitude greater than -30 nT and -40 nT. The result of the comparison is presented in Fig. 3.

Figure 3 shows that this interpretation is consistent with our physical picture of the phenomenon under study. Thus, the maximal number of samples with minimum of electron flux (cluster 0, black line) was really in 2009, when the number of magnetic storms was minimal. The fraction of background low fluxes of electrons (cluster 1, red line) is maximal, and the number of samples related to the cluster 4 (blue line), which corresponds to the maximal flux of electrons, by contrast, has its maximum in 2003, when there was a period of extremely high solar activity. Cluster 2 (green line) that we interpreted as events relevant to the main phase of storms is in good agreement with the time dependence of the number of storms in the bottom panel.
RESULTS AND DISCUSSION

Examples of the obtained results are presented in Figs. 4-6. Three time intervals with different solar and geomagnetic activity were selected – decay phase of solar activity (SA) cycle 23: February 1, 2006 – July 31, 2006 (Fig.4); anomalous minimum of SA in 2009 and the beginning of SA cycle 24: November 20, 2009 – June 30, 2010 (Fig. 5); maximum of SA cycle 24: September 1, 2013 – January 31, 2014 (Fig.6).

In all figures, the three upper diagrams present TS of logarithm of relativistic electrons (>2 MeV) flux measured at geostationary orbit by GOES satellite (blue, left axis) and the results of TS segmentation into 5, 4 and 3 clusters (cluster numbers from 0 to 4) with Kohonen SOM (red) and k-means algorithm (green), right axis. The fourth diagram presents TS of Kp-index multiplied by 10 (blue, left axis) and Dst-index in nT (black), right axis. The bottom diagram presents TS of SW speed (blue, left axis), B magnitude (red) and Bz (green), right axis.

Fig. 4. The results of clustering obtained for time range from February 1, 2008 till July 31, 2006.

Figure 4 corresponds to the decay period of solar activity cycle 23, when the average flux of electrons in the outer belt was high, and during the analyzed time period, ten significant electron flux enhancements were observed. One can see that when dividing into five clusters, clustering works satisfactorily both when K-means and Kohonen SOM are used, although the second clusterization looks more stable. When the number of clusters is reduced to 4, stability of clusterization with Kohonen SOM method also decreases, although the increase in the flux of electrons is still pointed out quite reliably. For three clusters, SOM method clusterization for the given period also looks adequately.
Fig. 5. The results of clustering obtained for time range from November 20, 2009 till June 30, 2010.

Fig. 6. The results of clustering obtained for time range from September 1, 2013 till January 31, 2014.
Figure 5 shows the results of clustering for the period of the abnormal minimum of SA (2009 year, when the electron flux in OERB was abnormally low) and the beginning of the current growth phase of 24 SA cycle. As can be seen from the figure, during this time period, the main conclusions regarding the quality of clusterization are the same – Kohonen SOM method works better than K-means, and five clusters show the situation in the Earth’s magnetosphere more clearly. As figure 5 shows, the segmentation obtained by k-means algorithm is more sensitive in case of very low values of the electron flux. The main result of the study of this period is that clustering works also during the SA minimum at low OERB electron fluxes.

In Figure 6, one can see the results of clustering for the period of maximum of SA cycle 24 – the current cycle of solar activity. Figure 6 shows that compared to the two time periods discussed above, during SA maximum clusterization using SOM algorithm becomes less stable and less explicable from the physical point of view. We assume that this is connected with the significant fraction of sporadic increases in the solar wind, and therefore with strong magnetic storms and variations of electron fluxes in OERB. This may require separating out a special type of dynamics (a special cluster). During SA decline and in the minimum of SA, the main contribution to geomagnetic activity and electron fluxes is given by recurrent solar wind streams from coronal holes.

CONCLUSION

The multi-dimensional time series consisting of the values of logarithm of electron flux in OERB, parameters of SW, IMF and geomagnetic indexes, with delay embedding to the depth of 24 hours, was split into three, four, and five clusters (types of segments) with Kohonen self-organizing map and with k-means algorithm.

The obtained results were analyzed for different time intervals – for decay, minimum and maximum of solar activity cycle. The following conclusions can be made:

1. The segmentation that was best corresponding to physically different states of the OERB, was obtained by the Kohonen self-organizing map with 5 clusters, 16×12 cells.
2. Clustering methods, if properly used, can give adequate results for different periods of solar and geomagnetic activity.
3. Segmentation obtained by k-means algorithm is usually more sensitive at low values of the electron flux, but less stable in respect to high-frequency switching from one cluster to another and back.
4. The quality of clusterization might possibly depend on the contribution of recurrent SW fluxes to geomagnetic storms and partly on the level of the electron flux.

Summarizing, segmentation of multi-dimensional time series with clustering algorithms is able to separate physically different situations. This may help scientists to understand outer ERB dynamics. This may also help to improve forecasts of geomagnetic activity and electron flux, if the forecasts are made separately for each type of dynamics (cluster).

ACKNOWLEDGEMENT

The authors thank the teams of ACE and GOES projects and WDCC2 Kyoto for the possibility to access and use the data of their experiments.

REFERENCES

Iucci, N., A.E. Levitin, A.V. Belov et al. (2005), Space weather conditions and spacecraft anomalies in different orbits, Space Weather, 3(1), S01001.
Pilipenko, V., N. Yagova, N. Romanova, and J. Allen, (2006), Statistical relationships between the satellite anomalies at geostationary orbits and high-energy particles, Advances in Space Research, 37(6), 1192–1205.