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Neural Network Prediction of Daily Relativistic Electrons Fluence in the Outer Radiation Belt of the Earth: Selection of Delay Embedding Method*

Roman Batusov[1,2], Sergey Dolenko[1], and Irina Myagkova[1]

[1]D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

[2]Physics Department, M.V.Lomonosov Moscow State University, Moscow, Russia

dolenko@sinp.msu.ru, irina@srd.sinp.msu.ru

Abstract

Prediction of the time series of relativistic electrons fluence in the outer radiation belt of the Earth encounters problems caused by complexity and non-linearity of the "solar wind – the Earth's magnetosphere" system. Artificial neural networks are a biologically inspired architecture that is a suitable tool to solve problems of such type. This study considers the dependence of the quality of prediction on the type and depth of delay embedding of input features.

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Keywords: delay embedding, time series, prediction, neural network, multi-layer perceptron, relativistic electrons of the outer radiation belt of the Earth

1 Introduction

Relativistic electrons flux of the Outer Radiation Belt of the Earth is one of the main factors of space weather since they may be harmful for spacecraft operations (e.g. (Cole, 2005), (Iucci, et al., 2005) and references there). The Earth's Radiation Belts (ERB) are the part of the Earth's magnetosphere, and they determine the radiation environment in the near-Earth space. The radiation environment at geosynchronous orbit (about 35 thousand km altitude – the outer boundary of the radiation belts) is of particular interest due to the large number of satellites populating this region. Relativistic electrons of the outer ERB are called "killer electrons" since the electronic components of spacecraft can be damaged, resulting in temporary or even complete loss of spacecraft (Dorman, et al., 2005).

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In the paper (Baker, et al., 1990) it has been found that integral day values of the fluxes – daily fluences of electrons with energy >2 MeV, measured at geosynchronous orbit, could be predicted one day ahead, using a linear filter with solar wind speed at the input. Later on, during elaboration of REFM (Relativistic Electron Forecast Model), this method was developed further for the purpose of increasing prediction quality and horizon. Prediction carried out with the help of REFM is presented at the portal (Space Weather Prediction Center, n.d.). Experimental values of electron fluence, which the prediction is compared to, are obtained in the experiment at spacecraft of GOES (Geostationary Operational Environmental Satellite) series, which were designed for monitoring of the environment (National Oceanic and Atmospheric Administration, n.d.).

An alternative approach to prediction of relativistic electron fluence in the outer ERB is based on use of artificial neural networks (ANN). This approach is used in the models presented in (Koons & Gorney, 1990) (Fukata, et al., 2002) (Ling, et al., 2010) to predict RE fluence at geostationary orbit. The authors of this study also have experience on predicting electron flux on geostationary orbit, both for hourly flux values (Myagkova, et al., 2015), (Efitorov, et al., 2016), (Myagkova, et al., 2016) and for daily fluences (Efitorov, et al., 2016).

It should be noted that the outer ERB is a complex dynamic system, it depends on the condition of the interplanetary environment – on solar wind (SW) velocity, on the values of components of the interplanetary magnetic field (IMF), geomagnetic disturbances etc. The processes in the outer ERB most likely have relaxation and nonlinear character. It leads to the fact that outer ERB has "memory", i.e. that its instant state is not completely determined by instant values of external parameters, and the duration of the "memory" and relaxation processes for radiation belts can change. This gives us ground for a more detailed research of how far back in time values should be taken into account for prediction of daily electron fluences in the outer ERB.

2 Data Sources and Preparation

As input data for making predictions of daily fluences of relativistic (E>2 MeV) electrons at geostationary orbit, we used time series of daily aggregated values of the following physical quantities:

- 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}) and SW temperature (measured in K)
- IMF vector parameters in same point L1 (measured in nT): Bx, By, Bz (IMF components in GSM system) and B amplitude (IMF modulus)
- Geomagnetic indexes: equatorial index Dst (measured in nT) and global geo-magnetic index Kp (dimensionless)
- Average daily fluence of relativistic electrons with energies >2 MeV at geostationary orbit (measured in $(cm^2 \cdot s \cdot sr)^{-1}$).

The source of the data on the SW and IMF parameters were the measurements performed continuously onboard the Advanced Composition Explorer (ACE) spacecraft (ACE Project Team, n.d.). The data on geomagnetic indexes was obtained from (World Data Center for Geomagnetism, n.d.), which provides official data for the values of geomagnetic indices, used worldwide for scientific research and practical applications. The data on relativistic electron flux was obtained from GOES project (NOAA National Centers for Environmental Information, n.d.).

Each variable was initially measured with a smaller time period, so, before being used, the data was aggregated to give time series with daily step, by averaging and/or by calculating daily minimum and maximum values of some variables (chosen based on physical considerations). Now, SW parameters and electron fluence have a wide dynamical range (more than 6 orders of magnitude), so instead of the real values of these variables, their logarithmic values were used. Also, to account for yearly