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Real-time Prediction of the Dst Index from ACE Solar Wind Data Using Elman Recurrent Neural Network

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Chapter 1 Introduction

1.1 Purpose of this Document

This is a manual document for making real-time prediction of the Dst index from ACE solar wind data with the Elman recurrent neural network models. This document describes how the software can access and process ACE solar wind data and how the software can make, display, and evaluate prediction. Therefore, the document will enable to maintain the web page of Real-Time Prediction of Geomagnetic Storm running at the Solar-Terrestrial Physics Division, Danish Meteorological Institute.

It must be emphasized that the network models employed here were all developed by Jian-Guo Wu during his Ph.D studies in Lund University, Sweden.

1.2 Purpose and Scope of the Software

The software can carry out the tasks as below:

- Fetch ACE solar wind plasma and interplanetary magnetic field data from NOAA/SEC
- Process the fetched solar wind data:
  - Delete text in data files
  - Make interpolation (polynomial) for data gaps
  - Average 1 minute data to hourly data
  - Calculate a variety of solar wind parameters
  - Normalize all the solar wind parameters to the range [-1,1]
- Make prediction with developed neural network models

  - Present input data to trained network models
  - Find the mean output from the optimally trained network models
  - De-normalize the normalized mean prediction into Dst (nT)

- Get the provisional Dst from the World Data Center-C2 for comparison

- Plot the ACE solar wind data, predicted and provisional Dst index

The software programs are written in C except that the plot routines are written in IDL. The prediction is made 1 hour in advance. For the details of the developed neural network models and the study of solar wind-magnetosphere coupling using neural networks, please refer to (*Wu*, 1997; *Wu and Lundstedt*, 1996, 1997a, 1997b; *Wu et al.*, 1998, and the references therein).

Chapter 2 User and Software Requirements

2.1 User Requirements

2.1.1 Product Perspective

The software programs are exploited for making real-time predictions of the magnetic storm index, Dst and enable in real-time to regularly display and update predictions on the web site of Solar-Terrestrial Physics Division. To know in details about the geomagnetic storm and the index Dst, please refer to the papers by (em Mayaud, 1980; em Gonzalez et al., 1994) and to, e.g., the AGU monograph *Magnetic Storms* (1998) and the book *Introduction to Space Physics*, edited by *Kivelson and Russell* (1995). For information of the ACE satellite, please visit the web http://www.gsfc.nasa.gov/ace/ace.html.

2.1.2 User Characteristics and General Constraints

Users of the software should only be staff at the DMI. Since the neural network models were developed by Jian-Guo Wu in Lund University, users outside the DMI must contact the DMI and Dr. Jian-Guo Wu as well as Dr. Henrik Lundstedt in the Lund Space weather Center to get the permission.

2.2 Software Requirements

2.2.1 Computer Capability Requirements

Two neural network models are provided for making real-time prediction, and each model requires about 10 M-bytes hard disk space. It apparently needs more disk space to keep most of historical events in the data base or to keep the prediction for the past years. Roughly speaking, each network model requires 1 M-bytes disk to make prediction for one month.

2.2.2 Software Constraints

The developed software programs are written in C except the plot routines in IDL. Therefore, a C complier and IDL must be available for the computer platform where the real-time prediction will be made. The real-time prediction is made as a gif file, which is required to have *xv* installed to view the prediction.

Chapter 3 Description of Software

3.1 Installation of Software

The software package and all the necessary ASCII data files are located in the well-organized directories. The relative location of the directories of programs and ASCII data files have been taken into account in unix script programs. The two models are used to make predictions of Dst, one (I) with the inputs of B, By, Bz, N, V, and the other (II) with the inputs of B, Bs, N, V with $\tau = 4h$. Here B is the magnitude of the interplanetary magnetic field (IMF), By and Bz are y-component and z-component (in GSM coordinate system) of the IMF, N is the solar wind number density, and V is the solar wind speed. τ is the length of the input layer in a neural network.

3.2 Description of Software Routines

The models are trained Elman recurrent neural networks. Elman networks are two-layer backpropagation networks with feedback connections from the hidden layer to its input (*Elman*, 1990). Hence, the input layer consists of two parts: the true input units and the context units. The context units simply hold as a copy of the activations of the hidden units from the previous time step. Thus, the network can integrate temporal information dating back to the initial state. It is this fact that results in the nonlinear memory capacity of the network, like any other architectures of recurrent networks. The feedback connections are fixed at 1.0 and are not subject to weight updating. The modifiable connections are all feed-forward, and can be trained using conventional gradient-descent method. A more detailed algorithm for the Elman network model was given by *Wu* (1997) and *Wu and Lundstedt* (1997a, 1997b), including implementation of Elman networks.

For the Model I with the inputs of B, By, Bz, N, V, the unix script for making real-time prediction is *pred_mod29a.exe*. For the Model II with the inputs of B, Bs, N, V with $\tau = 4h$, the unix script for making real-time prediction is *pred_mod18a_1c1.exe*. Each unix script includes many function blocks. The two scripts are identical in terms of function blocks. Each block has been elaborated inside the scripts. The software routines in each block are described below in more details.

- Fetch ACE real-time solar wind data from NOAA/SEC (ftp.sel.noaa.gov)

  This block is a unix script of automatic internet file transfer program.

- Delete text and read data from the retrieved data file

  deltxt_swemag is used to delete the text in the retrieved ACE IMF data file (*ace_mag_1m.txt*) from NOAA/SEC.

  deltxt_swepam is used to delete the text in the retrieved ACE plasma data file (*ace_swepam_1m.txt*) from NOAA/SEC.

- Read the latest fetched real-time data onto the existing data.

  read_acemg_1m is used to read the latest retrieved IMF data (*ace_mag_1m.txt*) onto the existing IMF data (*ace_mag_1mold*).

  read_swepam_1m is used to read the latest retrieved solar wind plasma data (*ace_swepam_1m.txt*) onto the existing plasma data (*ace_swepam_1mold*).

  The data are kept to span only 4 days here (This can easily be changed, of course). The longer data, the more difficult will be the interpolation for gaps in the next step. To span as long as 4 days of data, one must fetch at least 4 days of data manually at the very beginning of running the script in order to create the two data files *ace_mag_1mold* and *ace_swepam_1mold.*

- Keep real-time data in the database.

  The data (*ace_mag_1mold* and *ace_swepam_1mold*) serve as the existing data for the next run.

- Fill data gaps by polynomial interpolation.

  polint_acemg is used to make polynomial interpolation for gaps in the IMF data.

  polint_swepam is used to make polynomial interpolation for gaps in the plasma data.

  The gaps and bad records data are both considered as gaps and thereby interpolated. It must be aware that sometimes *polint_acemg* and *polint_swepam* can result in wrong values (either very big or very small) to fill gaps and/or bad records data if the gaps and/or bad records data are very long, e.g. 6

hours. Therefore, the prediction after long gaps and/or bad records data should not be trusted (for at least 10 hours). This is also due to the requirement for the initial values of the context units in the Elman network. It is therefore recommended that one use linear interpolation to fill gaps or to supersede bad data records and use polynomial interpolation to get extrapolation for gaps or bad data records to show up at the end of data flow. This could avoid the problem.

- Average to hourly data from solar wind data with 1 minute resolution

  aver_ace1m_1hf is used to average 1 minute resolution data to hourly data.

  The developed neural network models are based on hourly solar wind data. This is why the data must be averaged to hourly resolution.

- Calculate various solar wind parameters.

  cal_cpfs is used to calculate a variety of solar wind parameters.

  The resultant data file contains data in the sequence of columns: Year, Month, Day, Modified Julian Day, Seconds of the Day, Bx, By, Bz (GSM), $B, N, V, VBz, P^{0.5}$, ε, $Bs, VBs, P, P^{0.25}VBs, P^{1/3}VBs$, $P^{0.5}VBs$, PCP, Temperature (ion), latitude, longitude. PCP is the polar cap potential. Please refer to (*Wu*, 1997; *Wu and Lundstedt*, 1997a, 1997b) for the specification and expression of these solar wind parameters.

- Normalize all the solar wind parameters to the range [-1,1].

  normalize is used to normalize all the solar wind parameters to the range [-1,1].

  In one of the input files to *normalize*, *maxmin_orig_der*, the first and second rows are respectively the maxima and minima of the parameters of B, By, Bz (GSM), N, V, VBz, $P^{0.5}$, ε, $Bs, VBs, P, P^{0.25}VBs, P^{1/3}VBs, P^{0.5}VBs, PCP$.

- Generate input data file to the two neural network models

  gen_inputs_mod29a is used to generate input data to the Model I.

  gen_inputs_mod18a_c1 is used to generate input data to the Model II.

  In the file *ace_sw_1h_der_norm*, the data are in the sequence of columns: Year, Month, Day, Modified Julian Day, Seconds of the Day, Bx, By, Bz (GSM), $B, N, V, VBz, P^{0.5}$, ε, $Bs, VBs, P, P^{0.25}VBs, P^{1/3}VBs$, $P^{0.5}VBs$, PCP. The order is exactly the same as in the file *maxmin_orig_der*.

- Make prediction with developed neural network models.

  train_elm_adp is compiled from the source C code of an Elman recurrent neural network model. The source C code was completely made by Jian-Guo Wu in Lund University.

  The file *tmod29a_run* is the input file to *train_elm_adp* for the Model I and is used to obtain 4 possibly optimal output from the developed network model. The optimization comes from validation of the network prediction in constructing the model.

  The file *tmod18a1c1_run* is the input file to *train_elm_adp* for the Model II and is used to obtain 4 possibly optimal output from the developed network model.

  aver_outputs is used to average the 4 outputs from the model.

  denorm_Dst is used to de-normalize the output and obtain Dst value in nT.

  In the file *maxminp*, the first and second rows are respectively the maxima and minima of the parameters of B, F, Bx, By, Bz (GSM), σ_B, σ_F, σ_{Bx}, σ_{By}, σ_{Bz}, N, V, Dst in the data of the solar wind and Dst which were used to construct the network model.

- Fetch the provisional Dst from World Data Center C2 for Geomagnetism (http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/dst1/q/Dstqthism.html).

  The provisional Dst is used for comparison with the predicted Dst. The unix script is *wgetdst.exe*. In the script *deltxt_dsthtml* is used to extract the provisional Dst from the HTML file *Dstqthism.html* fetched by *kib/bin/IP22/wget* from the WDC-C2.

- Plot prediction results and solar wind inputs.

  plotsw_dstgif29a.pro is the plotting routine written in IDL for the Model I.

  plotsw_dstgif18a_1c1.pro is the plotting routine written in IDL for the Model II.

  The ACE solar wind data, predicted and provisional Dst index are plotted as a gif (or postscript) file. The gif file serves as the image to be loaded on the target web site.

The unix command *crontab* is used to invoke the unix scripts *pred_mod29a.exe*, *pred_mod18a_1c1.exe*, and *wgetdst.exe* at a regular time interval. Therefore, all the rountines in the unix scripts will carry out their tasks regularly and eventually produce a real-time prediction of Dst. This prediction as a gif image is then loaded on the target web site at a regular time interval as well. As such, people can see a real-time prediction of Dst through the target web site (Solar-Terrestrial Physics Division, DMI).

3.3 Example Run

The 2 examples of real-time prediction are shown in Figures 1 and 2 for quiet and disturbed geomagnetic activity.

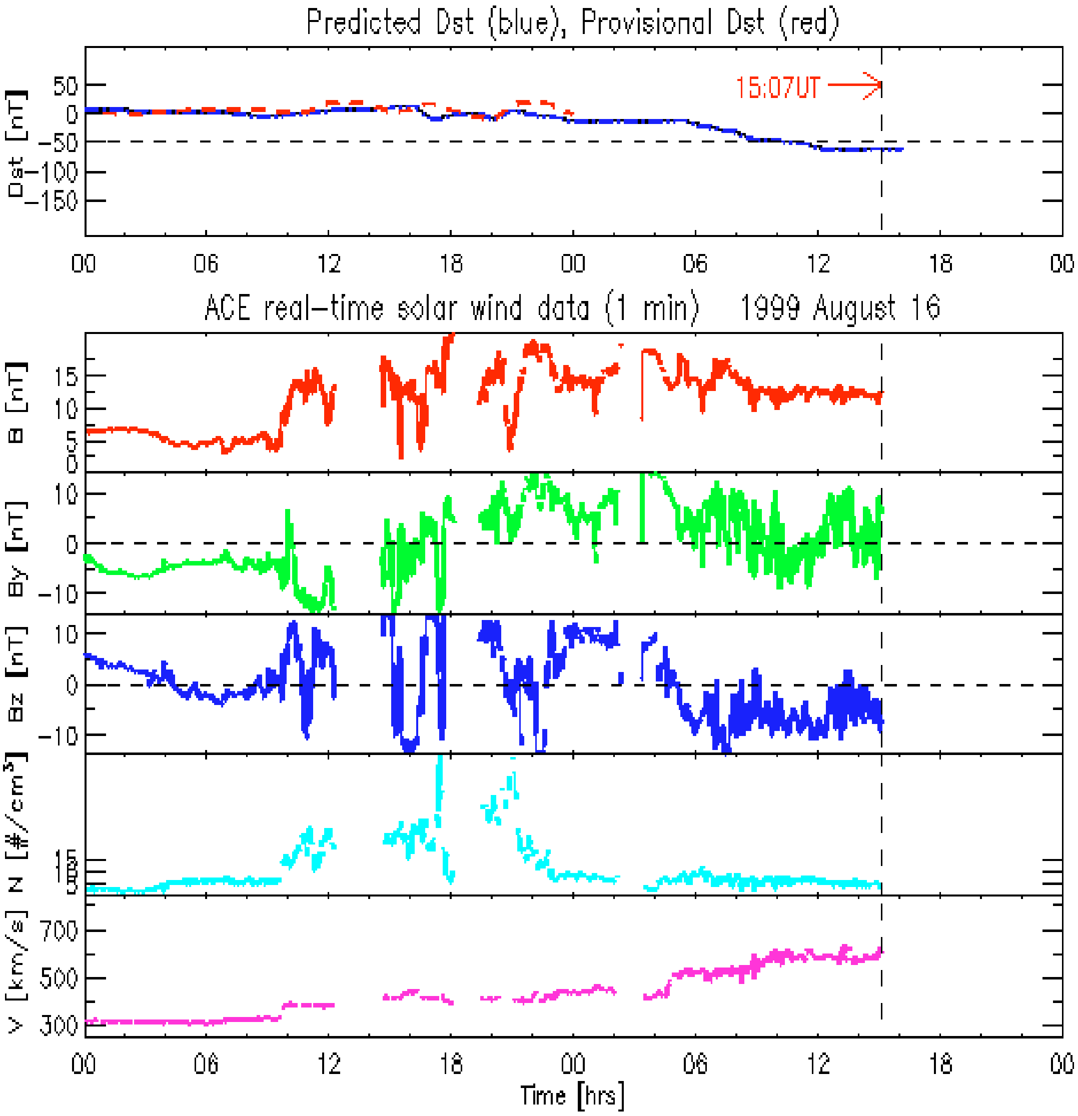

Figure 1. The 1 hour ahead prediction for quiet geomagnetic activity from the Model I.

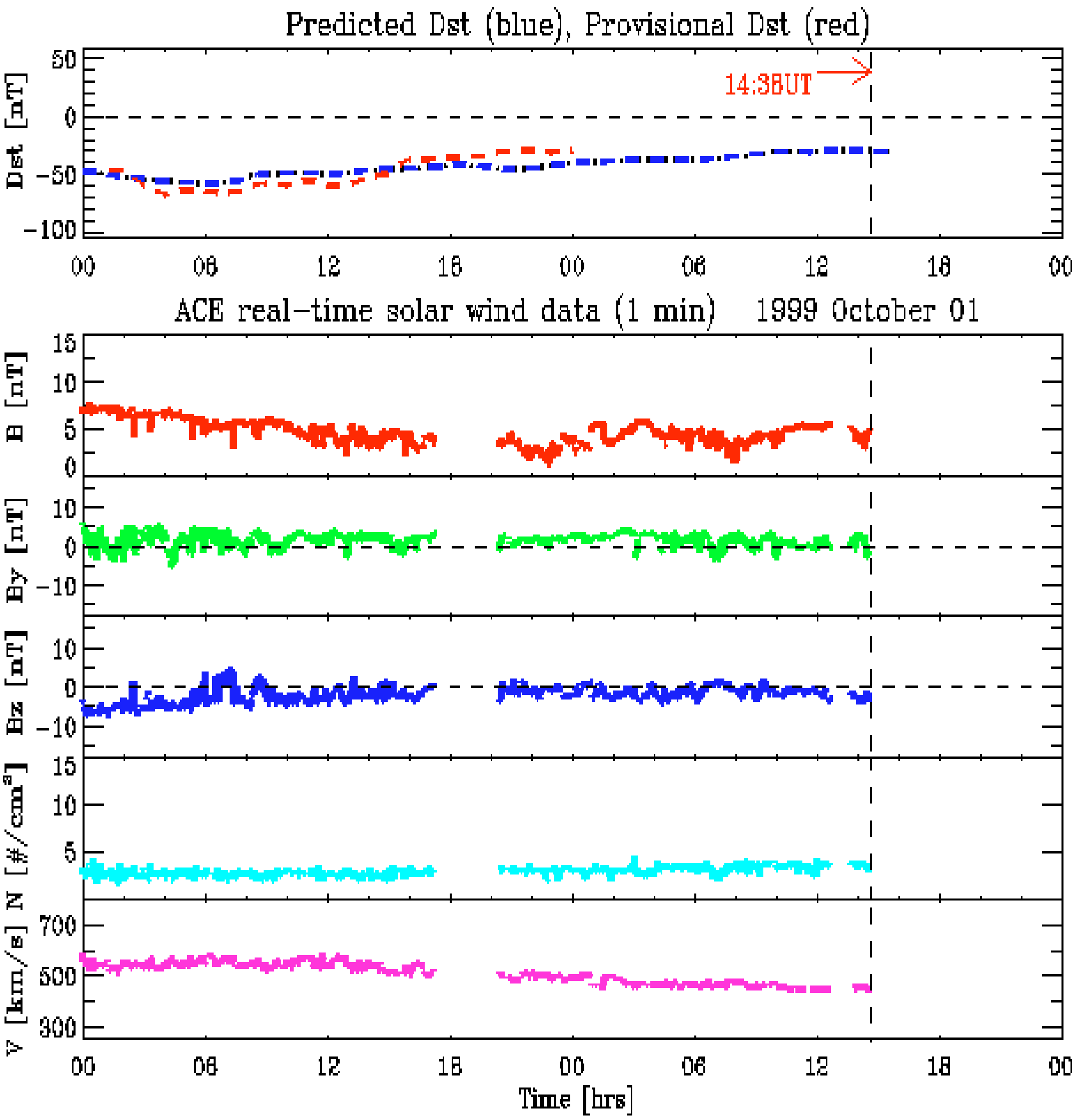

Figure 2. The 1hour ahead prediction for disturbed geomagnetic activity from the Model I.

The prediction of the month of 1999 September for Space Weather Campaign is presented in Figures 3 and 3.

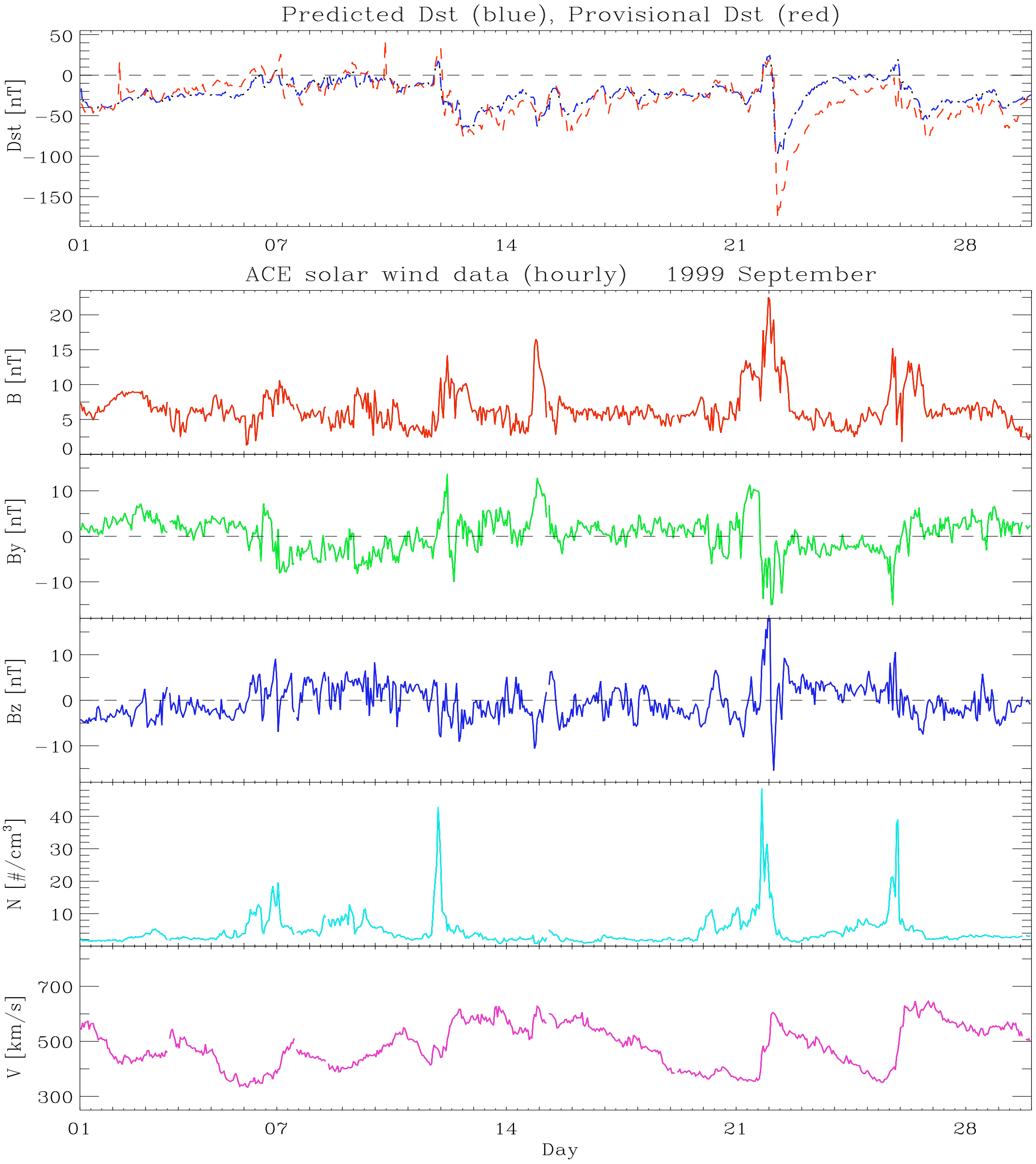

Figure 3. The 1hour ahead prediction from the Model I for September 1999.

To get Figures 3 and 4, one can follow the unix script *pred29a_month.exe* for the Model I and *pred18a_1c1_month.exe* for the Model II. One can look into the script for more detailed specification. The blocks are organized in a similar way to the script for real-time prediction.

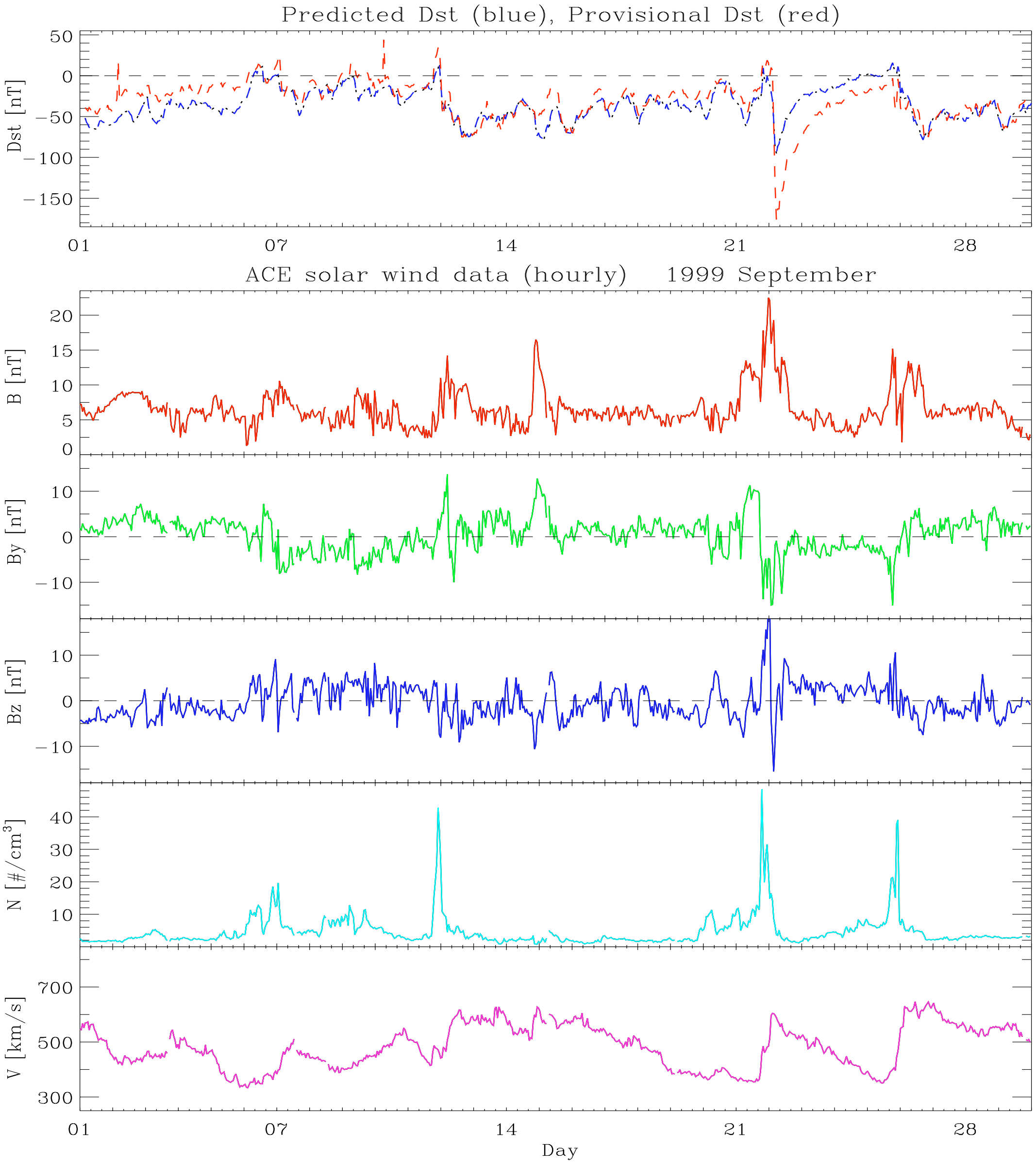

Figure 4. The 1hour ahead prediction from the Model II for September 1999.

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